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MATERIALS DATA HANDBOOK

Aluminum Alloy 6061

(2nd Edition)

Revised by

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May 1972

CR-123772.

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Contract No. NAS8-26644

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PREFACE

The revised edition of the Materials Data Handbook on the aluminum alloy 6061 was prepared by Western Applied Research & Development, Inc. under contract with the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama. It is a revised and updated version of the Handbook originally prepared by the Department of Chemical Engineering and Metallurgy at Syracuse University, July 1966.

It is intended that this Handbook present, in the form of a single document, a summary of the materials property information presently available on the 6061 alloy.

The Handbook is divided into twelve (12) chapters. The scope of the information presented includes physical and mechanical property data at cryogenic, ambient and elevated temperatures, supplemented with useful information in such areas as material procurement, metallurgy of the alloy, corrosion, environmental effects, fabrication and joining techniques. Design data are presented as available, and these data are complemented with information on the typical behavior of the alloy. The major source used for the design data is the Department of Defense document, Military Handbook-5A.

Information on the alloy is given in the form of tables and figures, supplemented with descriptive text as appropriate. Source references for the information presented are listed at the end of each chapter.

Throughout the text, tables, and figures, common engineering units (with which measurements were made) are accompanied by conversions to International (SI) Units, except in the instances where double units would over-complicate data presentation, or where SI units are impractical (e.g., machine tools and machining). In these instances, conversion factors are noted. A primary exception to the use of SI units is the conversion of 1000 pounds per square inch to kilograms per square millimeter rather than newtons, in agreement with the ASTM that this unit is of a more practical nature for worldwide use.

ACKNOWLEDGMENTS

The second edition of "Materials Data Handbook: Aluminum Alloy 6061" was prepared by Western Applied Research & Development, Inc. under Contract No. NAS8-26644 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Astronautics Laboratory, Materials Division of the George C. Marshall Space Flight Center with Mr. Wayne R. Morgan acting as Project Manager.

Sincere appreciation is tendered to the many commercial organizations and Government agencies who have assisted in the preparation of this document.

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TABULAR ABSTRACT

Aluminum Alloy 6061

TYPE:

Wrought, heat treatable aluminum alloy

NOMINAL COMPOSITION:

Al-1.0Mg-0.6Si-0.27Cu-0.25Cr

AVAILABILITY:

Bare and clad sheet and plate, rod, bar, wire, tube, extruded shapes, pipe, forgings and forging stock

TYPICAL PHYSICAL PROPERTIES:

Density	2.70 g/cm^3 at 20°C
Thermal Conductivity (O temper)	0.43 cal/cm/cm^2/sec/°C at 25°C
(T6 temper)	0.40 cal/cm/cm^2/sec/°C at 25°C
Av. Coeff. of Thermal Expansion	23.4 μcm/cm/°C (20–100°C
Specific Heat	0.23 cal/g °C at 100°C
Electrical Resistivity (O temper)	3.7 microhm-cm at 20°C
(T6 temper)	4.0 microhm-cm at 20°C

TYPICAL MECHANICAL PROPERTIES:

F_{tu} (O temper)	18.0 ksi (12.7 kg/mm^2)
(T6 temper)	45.0 ksi (31.6 kg/mm^2)
F_{ty} (O temper)	8.0 ksi (5.6 kg/mm^2)
(T6 temper)	40.0 ksi (28.1 kg/mm^2)
e(2 in, 50.8 mm) (O temper)	30 percent
(T6 temper)	17 percent
E (tension)	10.0 x 10^3 ksi (7.0 x 10^3 kg/mm^2

FABRICATION CHARACTERISTICS:

Weldability	Fusion: good if proper procedures are used; Resistance: special practices required
Formability	Excellent in annealed condition; also can be formed in T4 temper
Machinability	Excellent in T4 and T6 tempers

COMMENTS:

A versatile aluminum alloy having moderate strength and good resistance to corrosion.

SYMBOLS

a	One-half notch section dimension
A	Area of cross section; "A" basis for mechanical property values (MIL-HDBK-5A)
Å	Angstrom unit
AC	Air cool
AMS	Aerospace Material Specifications
Ann	Annealed
ASTM	American Society for Testing Methods
Av or Avg	Average
B	"B" basis for mechanical property values (MIL-HDBK-5A)
b	Subscript "bending"
bcc	Body centered cubic
BHN	Brinell hardness number
br	Subscript "bearing"
Btu	British thermal unit(s)
°C	Degree(s) Celsius
c	Subscript "compression"
CD	Cold drawn
CF	Cold finished
cm	Centimeter
c_p	Specific heat
CR	Cold rolled
CW	Cold worked
CVM	Consumable vacuum melted
D or Dia	Diameter
DPH	Diamond pyramid hardness
e	Elongation in percent
E	Modulus of elasticity, tension
E_c	Modulus of elasticity, compression
e/D	Ratio of edge distance to hole diameter
E_s	Secant modulus
E_t	Tangent modulus
eV	Electron volt(s)
°F	Degree(s) Fahrenheit
f	Subscript "fatigue"
F_{bru}	Bearing ultimate strength
F_{bry}	Bearing yield strength

fcc	Face centered cubic
FC	Furnace cool
F_{cy}	Compressive yield strength
F_{su}	Shear stress; shear strength
F_{tu}	Ultimate tensile strength
F_{ty}	0.2% tensile yield strength (unless otherwise indicated)
g	Gram
G	Modulus of rigidity
HAZ	Heat affected zone in weldments
hcp	Hexagonal close pack
hr	Hour(s)
HT	Heat treat
IACS	International annealed copper standard
in	Inch
ipm	Inches per minute
°K	Degree(s) Kelvin
K	Stress intensity factor; thermal conductivity
K_c	Measure of fracture toughness (plane stress) at point of crack growth instability
kg	Kilogram
K_{Ic}	Plane strain fracture toughness value
ksi	Thousand pounds per square inch
K_t	Theoretical elastic stress concentration factor
L	Longitudinal
lb	Pound
LT	Long transverse (same as transverse)
M	Bending moment
m	Meter
M	Subscript "mean"
Max	Maximum
ml	Milliliter
MIL	Military
Min	Minimum
mm	Millimeter
N	Cycles to failure
NSR	Notch strength ratio
NTS	Notch tensile strength
OQ	Oil quench
ppm	Parts per million
pt	Point; part

r	Radius
RA	Reduction in area; Rockwell hardness A scale
RB	Rockwell hardness B scale
RC	Rockwell hardness C scale
rpm	Revolutions per minute
RT	Room temperature
SA	Solution anneal
sec	Second
S-N	S = stress; N = number of cycles
Spec	Specifications; specimen
ST	Solution treat; short transverse
STA	Solution treated and aged
T	Transverse
t	Thickness; time
Temp	Temperature
typ	Typical
Var	Variable
VHN	Vickers hardness number
W	Width
WQ	Water quench

CONVERSION FACTORS

To Convert	To	Multiply By
angstrom units	millimeters	1×10^{-7}
Btu/lb/°F	cal/g/°C	1
Btu/ft²/sec/°F-inch	cal/g/cm²/sec/°C-cm	1.2404
circular mil	square centimeters	$5.067\ 075 \times 10^{-6}$
cubic feet	cubic meters	0.028 317
cubic feet/minute	liters/second	0.4720
cubic inches	cubic centimeters	16.387 162
feet	meters	0.304 800 609
foot-pounds	kilogram-meters	0.138 255
gallons (U.S.)	liters	3.785 411 784
inches	millimeters	25.4
ksi (thousand pounds per square inch	kilograms/square millimeter	0.70307
microns	millimeters	0.001
mils	millimeters	0.0254
ounces (avoir.)	grams	28.349 527
ounces (U.S. fluid)	milliliters	29.5729
pounds (avoir.)	kilograms	0.453 592 37
pounds/foot	kilograms/meter	1.488 16
pounds/cubic foot	grams/cubic centimeter	0.016 018 463
square feet (U.S.)	square meters	0.092 903 41
square inches (U.S.)	square centimeters	6.451 625 8

Temperature in °C = (°F – 32) (5/9)

Temperature in °K = °C + 273.15

Chapter 1

GENERAL INFORMATION

1.1 Aluminum alloy 6061 is a heat-treatable wrought alloy developed by the Aluminum Company of America in 1935 as a general purpose structural alloy. The main alloying elements are magnesium and silicon; the alloy also contains small additions of copper, chromium, iron, zinc, manganese and titanium. This alloy is the most versatile of the wrought heat-treatable alloys.

1.2 Aluminum 6061 combines the qualities of good resistance to corrosion and ease of fabrication with good mechanical properties. Its machinability rating is excellent and the alloy is readily welded by all conventional methods when proper techniques are used without lowering its resistance to corrosion. The alloy also exhibits excellent brazing characteristics in all tempers. Alloy 6061 is available in a full range of commercial sizes for sheet, strip, plate, bar, rod, forgings, rolled shapes, extrusions, tubing, pipe, wire, and rivets. It is also available as Alclad sheet and plate.

1.3 Aluminum 6061 is used for many applications because of its versatility. Typical areas are marine structures, machinery parts, aircraft fairing, large trailer bodies, screw machine products, architectural structures, aircraft landing mats and furniture, and liquid-rocket motors.

Chapter 1 - References

1.1 Alloy Digest, "Aluminum 6061" (Filing Code Al-3), Engineering Alloys Digest, Inc., New Jersey, November 1952.

1.2 Aerospace Structural Metals Handbook, Vol. II, "Non-Ferrous Alloys," V. Weiss and J.G. Sessler, Eds , ASD TDR 63-741, 1971 Edition.

1.3 Materials in Design Engineering, Materials Selector Issue, Mid-October, 1964.

1.4 Reynolds Metals Co., "The Aluminum Data Book," 1965.

1.5 Metals Handbook, Vol. 1, "Properties and Selection of Metals," 8th Ed., American Society for Metals, Metals Park, Ohio, 1961.

1.6 Harvey Aluminum, "Mill Products and Alloys," June 1967.

1.7 Olin Aluminum/Metals Div., "Olin Aluminum Mill Products and Casting Alloys," Product Data Bulletin.

Chapter 2

PROCUREMENT INFORMATION

2.1 General. Aluminum alloy 6061 is available in a full range of commercial sizes for sheet, strip, plate, rod, bar, forgings, tube, wire, pipe, extrusions, and structural shapes. Detailed tables of standard sizes and tolerances for the various products available are given in reference 2.1.

2.2 Procurement Specifications. Specifications that apply to the 6061 alloy as of May 1971 are listed in table 2.2 for various products and tempers.

2.21 NASA Specifications

2.211 MSFC-SPEC-144B, "Specification for Aluminum Alloy Forgings, Premium Quality, Heat Treated," dated March 31, 1964, Amendment No. 1, dated September 8, 1964. Prepared by George C. Marshall Space Flight Center. Custodian: NASA-MSFC. Specification applies to 6061-T4, 6061-T6, and 6061-T652 forgings for parts used in critical applications.

2.3 Major Producers of the Alloy (United States Only)

Aluminum Company of America
1501 Alcoa Building
Pittsburgh, Pennsylvania

Kaiser Aluminum and Chemical Sales, Inc.
919 North Michigan Avenue
Chicago, Illinois

Harvey Aluminum
General Offices
Torrance, California

Olin Aluminum/Metals Division
460 Park Avenue
New York, New York

Reynolds Metals Company
6601 West Broad Street
Richmond, Virginia

2.4 Typical examples of available forms, sizes, and conditions for various 6061 alloy products are given in table 2.4.

TABLE 2.2. — Procurement Specifications

Source	Refs. 2.4, 2.6, 2.7, 2.8				
Alloy	Al-6061				
Product	Temper	Military	Federal	ASTM	AMS
Bar, rod, shapes, tube (extruded)	O	-	QQ-A-200/D	B221-71	4160B
	T4	-	QQ-A-200/D	B221-71	4161B
	T6	-	QQ-A-200/D	B221-71	4150E
	F, T42, T62	-	-	B221-71	-
	T4510, T4511	-	-	B221-71	-
	T6510, T6511	-	-	B221-71	-
Bar, rod, wire, shapes (rolled or drawn)	O	-	QQ-A-225/8c	B211-71	4115B
	T4	-	QQ-A-225/8c	B211-71	4116C
	T6	-	QQ-A-225/8c	B211-71	4117C
	T42	-	QQ-A-125/8c	B211-71	-
	T451, T651	-	QQ-A-225/8c	B211-71	-
Sheet, plate (bare)	General	-	QQ-A-250d	-	-
	O	-	QQ-A-250/11d	B209-71	4025E
	T4	-	QQ-A-250/11d	B209-71	4026E
	T6	-	QQ-A-250/11d	B209-71	4027G
	T42	-	QQ-A-250/11d	B209-71	-
	T451	-	QQ-A-250/11d	B209-71	4043A
	T651	-	QQ-A-250/11d	B209-71	4053A
	F	-	QQ-A-250/11d	-	-
Sheet, plate (Alclad)	O	-	-	B209-71	4021C
	T4	-	-	B209-71	4022D
	T6	-	-	B209-71	4023D
	T42, T62	-	-	B209-71	-
	T451	-	-	B209-71	-
	T651	-	-	B209-71	4020
Pipe (extruded or drawn)	T6	MIL-P-25995A	-	B241-71	-
	T4, T6	-	-	B345-71	-
Clad pipe (extruded or drawn)	T6	-	-	B345-71	-
Forgings	T6	MIL-A-22771B	QQ-A-367g	B247-70	4127B
	T4	-	-	-	4146
Forging stock	T6	-	-	-	4127C
	T4	-	-	-	4146A
Armor plate	-	MIL-A-46027C	-	-	-
Structural shapes	T4, T6	MIL-A-25994	-	B308-70	-
Tube, seamless (drawn)	O	-	WW-T-700/6d	B210-70	4079B, 4080E
	T42	-	WW-T-700/6d	-	-
	T4	-	WW-T-700/6d	B210-70, B234-71	-
	T6	-	WW-T-700/6d	B210-70, B234-71	4082H
Tube, aircraft hydraulic	T4	MIL-T-7081D	-	-	4081C
	T6	MIL-T-7081D	-	-	4083F
Tube, round (welded)	O, T4, T6	-	-	B313-68	-
Impact Extrusions	O, F, T4, T6, T84	MIL-A-12545A	-	-	-
Rivets	T6	MIL-R-1150A-1	-	-	-
Rivet wire	O, H13, T6	-	QQ-A-430B	B316-71	-
Floor plate	O, F, T4, T6	MIL-F-17132B	-	-	-
Nails, wire, staples	-	-	FF-N-105-2	-	-

TABLE 2.4. – Typical Examples of Available Commercial Forms and Sizes

Source	Refs. 2.5, 2.9, 2.10		
Alloy	Al-6061		
Product	Condition	Finish	Dimensions
Coiled sheet, bare and Alclad	O, F	comm. mill	0.016-0.125 in (0.406-3.17 mm) thick; 0.5-60 in (1.27-152 cm) wide; 16- and 20-in (40- and 50-cm) arbor size.
Flat sheet, bare	O, T4, T6	comm. mill, skin quality	0.016-0.249 in (0.406-6.32 mm) thick; 3-60 in (7.6-152 cm) wide; 24-180 in (61-457 cm) lengths.
Flat sheet, Alclad	O, T4, T6	comm. mill, skin quality	0.032-0.249 in (0.812-6.32 mm) thick; 3-60 in (7.6-152 cm) wide; 24-180 in (61-457 cm) lengths.
Plate, bare	O, F, T4, T451, T6, T651	comm. mill	0.250-1.00 in (6.35-25.4 mm) thick; 6-72 in (15-183 cm) wide; 48-180 in (122-457 cm) lengths.
Plate, Alclad	O, T4, T451, T6, T651	comm. mill	0.250-1.00 in (6.35-25.4 mm) thick; 6-72 in (15-183 cm) wide; 48-180 in (122-457 cm) lengths.
Rounds	cold processed	etched, brightened, plastic-coated	3/32-3 in (0.24-7.6 cm) diam.
Hexagonals	cold processed	etched, brightened, plastic-coated	1/8-2 in (0.32-5.1 cm) diam.
Extrusion ingot	direct chill	-	4-7/16 to 11 in (11-28 cm) diam; 11-192 in (28-488 cm) lengths.
Extrusions, and structural shapes	O, T4, T6	-	<2-25 in (5.1-64 cm) circum. circle diam. 0.040-0.156 in (0.35-4.0 mm) min thickness.
Impact extrusions	O, T4, T6, T84	-	up to 14-in (36 cm) diam; up to 12-ft (3.7 m) lengths.
Round hollow bar, or hexagonal hollow bar	T6	-	1.0-4.0 in (2.5-10.2 cm) O.D. (or distance across flats); 10-14 ft (3-4.3 m) lengths.

Chapter 2 - References

2.1 Aluminum Standards & Data: 1970-71, The Aluminum Association, New York, 1970.

2.2 Aluminum Co. of America, "Alcoa Aluminum Handbook," 1962.

2.3 Aluminum Co. of America, "Alcoa Product Data - Specifications," Section A12A, July 1963.

2.4 1971 SAE Handbook, Society of Automotive Engineers, New York.

2.5 Olin Aluminum/Metals Div., "Olin Aluminum Mill Products and Casting Alloys," Product Data Bulletin.

2.6 Aerospace Material Specifications, Society Automotive Engineers, Inc., New York, latest Index, May 1971.

2.7 Index of Specifications and Standards, Part I, Alphabetical Listing, Dept. of Defense, latest Index, July 1971.

2.8 ASTM Standards, Part 6, "Light Metals and Alloys," 1971.

2.9 Harvey Aluminum, "Mill Products and Alloys," June 1967.

2.10 Harvey Aluminum, "Hollow Aluminum Screw Machine Stock," October 1970.

Chapter 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of 6061, in percent (ref. 3.2)

Cu	0.27	Mg	1.0
Cr	0.25	Si	0.6
Al - Balance			

3.111 Sheet and plate are available in the Alclad condition. Cladding material is Al-7072 alloy. Nominal composition of 7072 alloy, in per cent (ref. 3.12)

Zn	0.8-1.3	Mg	0.1 max
Si+Fe	0.7 max	Others	
Mn	0.1 max	Each	0.05 max
Cu	0.1 max	Total	0.15 max
Al - Balance			

The nominal cladding thickness per side is 5 percent of the total composite thickness for all sheet and plate thicknesses. The 6061 alloy is clad on both sides.

3.12 Chemical composition limits, in percent (ref. 3.13)

Si	0.40-0.80	Zn	0.25 max
Fe	0.7 max	Ti	0.15 max
Cu	0.15-0.40	Others	
Mn	0.15 max	Each	0.05 max
Mg	0.8-1.2	Total	0.15 max
Cr	0.04-0.35	Al	Balance

3.13 Alloying Elements. Magnesium and silicon are the primary alloying elements, with copper added for extra strength and chromium for extra strength, grain refinement, and improved resistance to corrosion. The primary precipitation-hardening agent is Mg_2Si. $CuAl_2$ also contributes to a limited extent to hardening. Ternary phase diagrams of Al-Mg-Si are shown in figure 3.131. The binary system for Al-Mg silicide is shown in figure 3.132, and the binary system for Al-Cr and Al-Cu in figure 3.133. The important eutectic temperatures are: Al-Cu, 548°C, and Al-Mg_2Si, 595°C (refs. 3.4, 3.5). An excess of Si lowers the resistance to corrosion appreciably (ref. 3.3). In general, the low total alloying content gives this alloy many characteristics of commercially pure aluminum, such as good resistance to corrosion and stress-corrosion and weldability, including fusion welding (ref. 3.6). Further corrosion protection is provided by cladding (see Section 3.111).

3.2 Strengthening Mechanisms

3.21 General. The alloy is strengthened by precipitation hardening and cold work. The precipitation hardening mechanisms are evident from the phase diagrams in figures 3.131 to 3.133. Because of the low alloying content, the solution-treated condition is very stable (ref. 3.6). On heating to the aging temperature, precipitation occurs in the form of submicroscopic particles, which represent obstacles to the plastic flow and thus cause hardening. The alloy can also be hardened by cold work, a general property of all aluminum alloys related to crystal structure and stacking-fault energy. Various processes utilize the effect of both operations, i.e., cold working in the solution-treated condition and subsequent aging, as well as cold working after aging.

3.22 Heat Treatment. Recommended heat treating procedures for the 6061 alloy are given below.

3.221 Annealing (O Condition). The annealing treatment is essentiall an overaging treatment. Heat to 413°C, hold 2 to 3 hours, followed by slow cool (28°C/hr) to 260°C (ref. 3.7). Intermediate anneals for the removal of cold work should be performed at 343°C. Time and cooling rate are not critical (ref. 3.7).

3.222 Solution Treatment (ref. 3.11)

Bare Products (except forgings):
Heat to 521° to 543°C, hold as per table 3.22, followed by rapid cold water quench.

Clad Sheet and Plate:
Heat to 516° to 538°C, hold as per table 3.22, followed by rapid cold water quench.

Forgings:
Heat to 516° to 543°C, hold as per table 3.22, follwed by rapid cold water quench.

3.223 Precipitation Treatments (Aging) (ref. 3.11)

Natural age to T4 condition (all products except forgings):
Hold as-quenched material at room temperature for 96 hours.

Artificial age to T6 condition (all products):
Heat T4 material to 171°C to 182°C, hold 7.5 to 8.5 hours. The cooling rate from the aging temperature is not critical. The designation is T62 if solution and aging treatments are performed by the user.

3.224 Cold work and combined treatments, together with solution and aging treatments for various products, are listed in table 3.224.

3.3 Critical Temperatures. Melting range is 582° to 649°C (refs. 3.10, 3.12). The oxidation resistance is generally good until the melting temperature is approached.

3.4 Crystal Structure. Face-centered cubic. The lattice parameter for pure aluminum is a_0 = 4.0491 (ref. 3.10).

3.5 Microstructure. The difference in appearance of the microstructure between natural and artificial aging can be developed by immersion etching with 2.5 percent HF and 5 percent H_2SO_4 in water, see figure 3.51. Recrystallization during heat treatment can also be readily recognized after the use of the HF—H_2SO_4 etch, figure 3.52. Reference 3.9 is recommended as an excellent source of information on the identification of constituents in aluminum alloys.

3.6 Metallographic Procedures. In general, mechanical polishing is preferred to electropolishing, especially where larger microconstituents are present and the material is relatively soft, because objectionable relief effects produced by the electrolytic polishing technique may cause a misinterpretation of the microstructure (ref. 3.8). For homogeneous alloys, and for those conditions containing only finely dispersed particles, the electrolytic method is excellent. Preparatory polishing on metallographic polishing papers 0 to 000 should be performed wet with a solution of 50 g paraffin in 1 liter kerosene to keep the specimen bright and avoid imbedding of grinding compound particles into the soft specimen surface. Rough polishing on a "kitten's ear" broadcloth at 250 to 300 rpm with heavy magnesium oxide powder is recommended (refs. 3.4 and 3.9).

An alternate and popular method consists of the following steps:

1) Wet polishing (flowing water with 240-grit silicon carbide paper at approximately 250 rpm.

2) Wet polishing with 600-grit silicon carbide paper at approximately 250 rpm.

3) Polishing with 9-μm diamond paste on nylon cloth at 150 to 200 rpm using a mild soap solution for lubrication.

4) Final polish on a vibratory polisher using a microcloth containing a slurry of methyl alcohol and 0.1-μm aluminum oxide powder. A slurry of 0.1-μm aluminum oxide powder in a 10-percent solution of glycerine in distilled water may also be used for this step.

Etching reagents have to be suited to the objective of the study. Keller's etch reveals microstructural details and grain boundaries satisfactorily. A 10-percent solution of NaOH gives better detail of the microstructural constituents but does not delineate the grain boundaries. Study of the "as polished" surface prior to etching may also give valuable information on the types of constituents present, especially when attention is paid to the colors of the various particles. Macroscopic studies for cracks, gross defects, forging lines, and grain structure should be made with the following etching solutions: 10-percent NaOH (cracks, gross defects); Tucker's etch, modified Tucker's etch, and Flick's etch. The etching solutions for revealing the macrostructure are given in table 3.61. Suggested etching reagents for revealing microstructure are given in table 3.62.

TABLE 3.1. – Soaking Time for Solution Treatment of 6061 Products

Source	Ref. 3.11			
	Soaking time, minutes (a)			
	Salt Bath (c)		Air Furnace (d)	
Thickness, inches (b, f)	min	max (alclad only) (e)	min	max (alclad only) (e)
0.016 and under	10	15	20	25
0.017 to 0.020 incl.	10	20	20	30
0.021-0.032 incl.	15	25	25	35
0.033-0.063 incl.	20	30	30	40
0.064-0.090 incl.	25	35	35	45
0.091 to 0.125	30	40	40	50
0.126 to 0.250 incl.	35	45	50	60
0.251 to 0.500 incl.	45	55	60	70
0.501 to 1.000 incl.	60	70	90	100
1.001 to 1.500 incl.	90	100	120	130
1.501 to 2.000 incl.	105	115	150	160
2.001 to 2.500 incl.	120	130	180	190
2.501 to 3.000 incl.	150	160	210	220
3.001 to 3.500 incl.	165	175	240	250
3.501 to 4.000 incl.	180	190	270	280

(a) Longer soaking times may be necessary for specific forgings. Shorter soaking times are satisfactory when the soak time is accurately determined by thermocouples attached to the load.

(b) The thickness is the minimum dimension of the heaviest section.

(c) Soaking time in salt-bath furnaces should be measured from the time of immersion, except when, owing to a heavy charge, the temperature of the bath drops below the specified minimum; in such cases, soaking time should be measured from the time the bath reaches the specified minimum.

(d) Soaking time in air furnaces should be measured from the time all furnace control instruments indicate recovery to the minimum of the process range.

(e) For alclad materials, the maximum recovery time (time between charging furnace and recovery of furnace instruments) should not exceed 35 minutes for gages up to and including 0.102 inch, and 1 hour for gages heavier than 0.102 inch.

(f) 1 inch = 25.4 mm.

TABLE 3.224. — Tempers and Treatments for Bare and Clad 6061 Products

Sheet	Plate	Rod, Bar, Wire (rolled or CF)	Rod, Bar, Shapes, Tube (extruded)	Tube (drawn)	Pipe	Rivet Wire and Rod	Die Forgings	Hand Forgings	Forging Stock	Structural Shapes (rolled or extruded)	Rolled Rings	
Source				Refs. 3.2, 3.7								
			F						F			As fabricated
O*	O*	O	O	O		O						413°C, 2-3 hr, cool 28°C/hr to 260°C
T4*	T4*	T4	T4	T4						T4		See Chapter 3, Section 3.222
T42*	T42*	T42	T42	T42								T4 heat treated by user
	T451*	T451										T4 + stress relief by stretching (a)
			T4510									Stress relief by stretching (b)
			T4511									Stress relief by stretching (c)
T6*	T6*	T6	T6	T6	T6		T6	T6		T6	T6	See Chapter 3, Section 3.223
			T62									T6 heated treated by the user
	T651*	T651										T6 + stress relief by stretching (a)
											T652	T6, stress-relieved by compressing
			T6510									Stress relief by stretching (b)
			T6511	T6511								Stress relief by stretching (c)
H12												Cold work to 1/4 hard condition
						H13						Cold work to 3/8 hard condition
		T89										ST+CW+artificial age
		T93										ST+artificial age+CW
		T94										ST+artificial age + CW
		T913										ST+artificial age + CW

* 6061 Alclad also

(a) 1.5 to 3 percent for sheet and plate
1 to 3 percent for rod, bar, shapes, and tube
0.5 to 3 percent for drawn tube

(b) No further straightening after stretching

(c) Minor straightening after stretching to comply with standard tolerances.

TABLE 3.61. – Etching Solutions for Revealing Macrostructure

Source	Ref. 3.4		
Alloy	6061		
Solution	Concentration (a)		Specific Use
Sodium Hydroxide	NaOH Water	10 g 90 ml	For cleaning surfaces, revealing unsoundness, cracks, and gross defects
Tucker's	HCl (conc.) HNO_3 (conc.) HF (48%) Water	45 ml 15 ml 15 ml 25 ml	For revealing structure of castings, forgings, etc.
Modified Tucker's	HCl (conc.) HNO_3 (conc.) HF (48%) Water	10 ml 10 ml 5 ml 75 ml	For revealing structure of all castings and forgings except high silicon alloys
Flick's	HCl (conc.) HF (48%) Water	15 ml 10 ml 90 ml	For revealing grain structure of duralumin type alloys. Surface should be machined or rough polished.

(a) All of these solutions are used at room temperature

TABLE 3.62. – Etching Reagents for Revealing Microstructure

Source	Ref. 3.5			
Alloy	6061			
Composition		Uses	Remarks	
NaOH Water	1 g 99 ml	General microstructure	Swab with soft cotton for 10 seconds	
NaOH Water	10 g 90 ml	General microstructure (micro and macro)	Immerse 5 seconds at 71°C, rinse in cold water	
Keller's (conc.) HF (conc.) HCl (conc.) HNO_3 (conc.) Water	 10 ml 15 ml 25 ml 50 ml	General microstructure (micro and macro) for copper bearing alloys	Use concentrated for macroetching; dilute 9:1 with water for microetching	
HF (conc.) H_2SO_4 (conc.) Water	5 ml 10 ml 185 ml	Grain structure, solution treated 6061. Will show difference between T4 and T6 material	Etch 30 seconds for grain boundary of T4 material; 60 seconds for T6 material. Also extent of recrystallization	

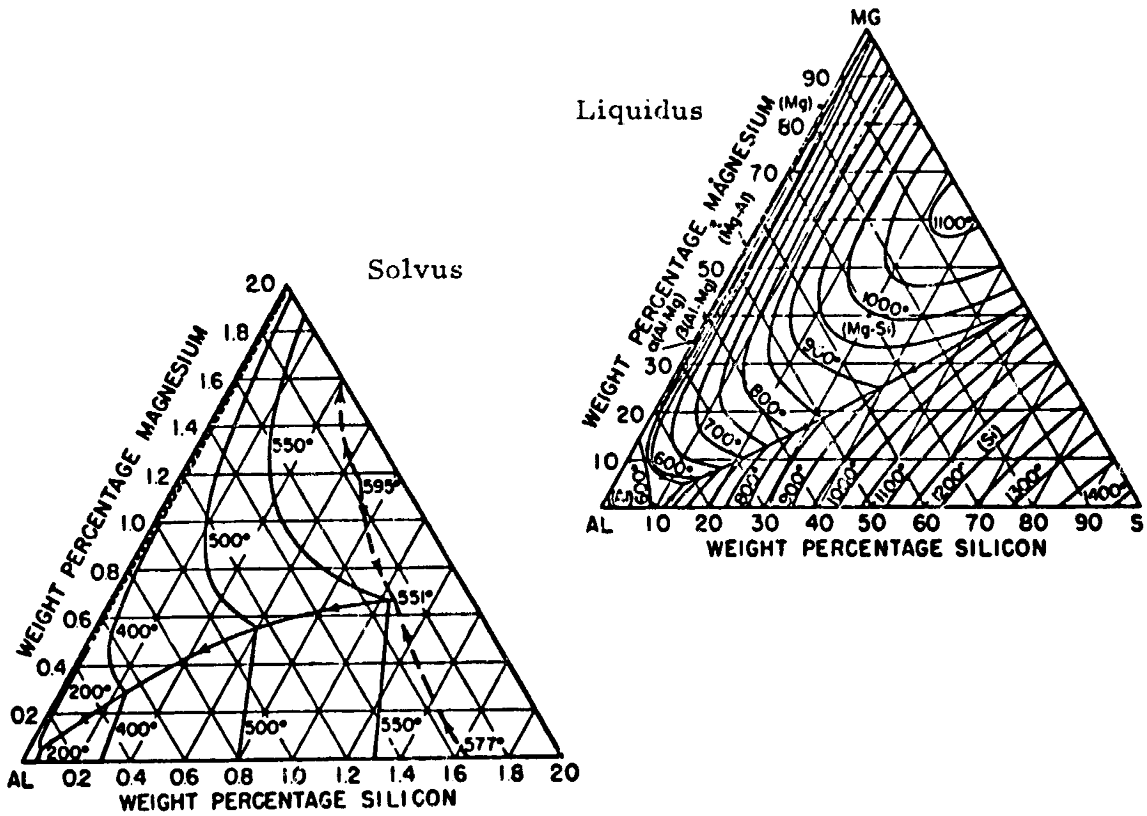


FIGURE 3.131. -- Aluminum-magnesium-silicon system.
(Ref. 3.4)

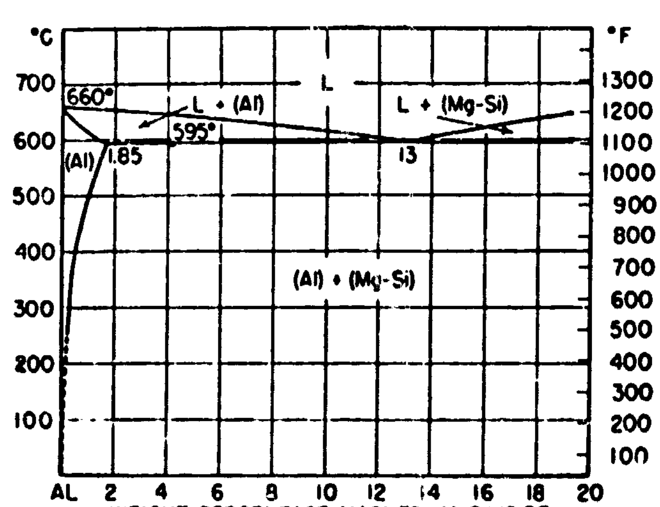
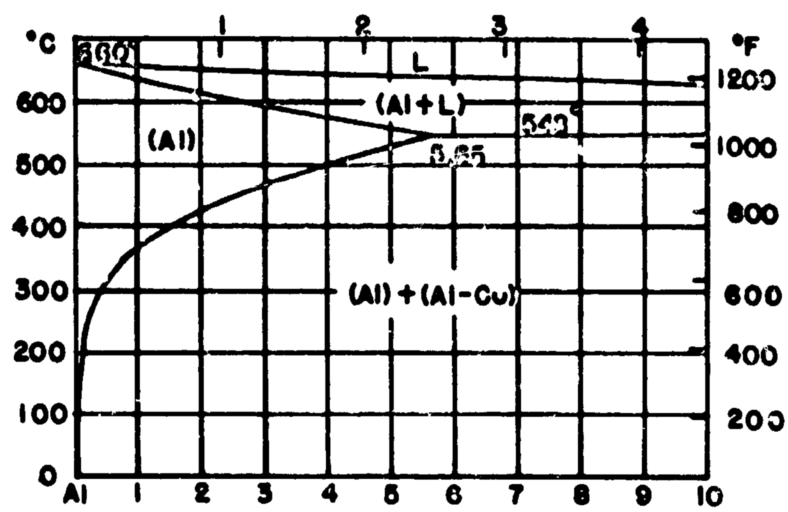
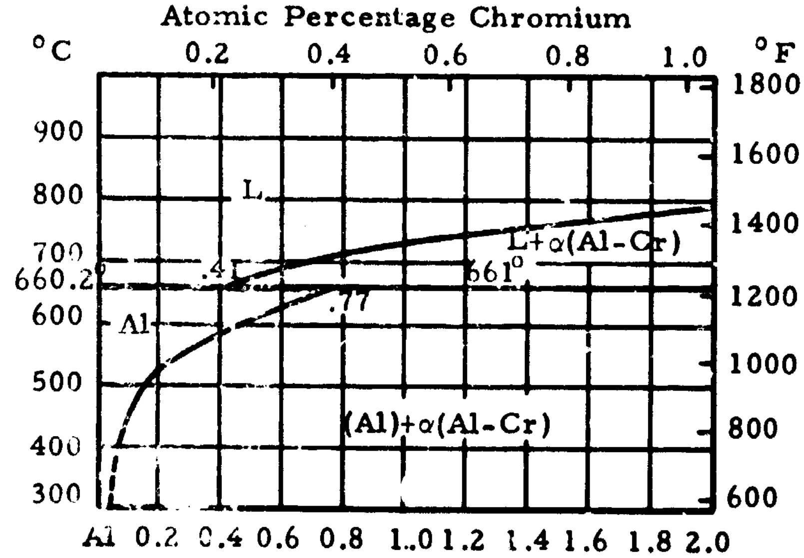


FIGURE 3.132. -- Binary section, aluminum-magnesium-silicide.
(Ref. 3.4)



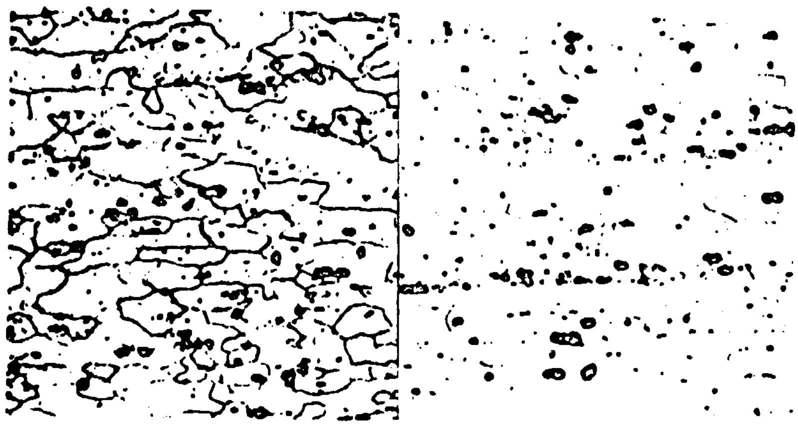
Aluminum—Copper



Aluminum - Chromium

FIGURE 3.133. -- Binary diagrams for aluminum-copper and aluminum-chromium systems.

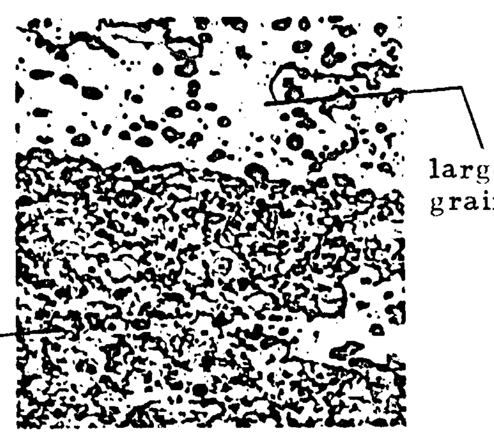
(Ref. 3.5)



T4 T6

Etch: $HF-H_2SO_4-H_2O$ 500X

FIGURE 3.51. – Natural aging (T4) and artificial aging (T6). (Ref. 3.8)



Etch: $HF-H_2SO_4-H_2O$ 250X

FIGURE 3.52. – Recrystallization during heat treatment. (Ref. 3.8)

Chapter 3 - References

3.1 Metals Handbook, 8th Ed., Vol. 2, "Heat Treating, Cleaning, and Finishing," American Society for Metals, Metals Park, Ohio, 1964.

3.2 Aluminum Standards & Data: 1970-71, The Aluminum Association, New York, September 1965.

3.3 J.A. Nock, Jr., "Commercial Wrought Aluminum Alloys," in Physical Metallurgy of Aluminum Alloys, American Society for Metals, Metals Park, Ohio, 1958.

3.4 W.L. Fink, et al., in Physical Metallurgy of Aluminum Alloys, American Society for Metals, Metals Park, Ohio, 1958.

3.5 E.H. Wright and L.A. Willey, "Aluminum Binary Equilibrium Diagrams," Alcoa Technical Paper No. 15, 1960.

3.6 W.H. Dennis, Metallurgy of the Non-Ferrous Metals, Sir Isaac Pitman & Sons, Ltd., 1960.

3.7 Reynolds Metals Co., "The Aluminum Data Book," 1965.

3.8 J.P. Vidosic, "Study of Phase Identification in Steel and Aluminum Alloys," Georgia Institute of Technology, Final Report, NASA Contract NAS8-5117, September 1963.

3.9 F. Keller and G.W. Wilcox, "Identification of Constituents of Aluminum Alloys," Technical Paper No. 7, Aluminum Co. of America, 1942.

3.10 Metals Handbook, 8th Ed., Vol. 1, "Properties and Selection of Metals," American Society for Metals, Metals Park, Ohio, 1961.

3.11 Military Specification, "Heat Treatment of Aluminum Alloys," MIL-H-6088E, February 1971.

3.12 1971 SAE Handbook, Society Automotive Engineers, New York.

3.13 ASTM Standards, Part 6, "Light Metals," American Society for Testing Materials, 1971.

Chapter 4

PRODUCTION PRACTICES

4.1 General. In the United States, aluminum and its alloys are produced from an ore of impure hydrated aluminum oxide known as "bauxite." Important sources of bauxite are located in Arkansas, Dutch Guiana, and Jamaica. The impure ore is converted into pure aluminum oxide (alumina) through a series of chemical processes. Oxygen is removed from the alumina by smelting in carbon-lined electric furnaces known as reduction pots. Pure molten aluminum is deposited at the bottom of the pot, and is periodically siphoned off and poured into molds to form "pigs" and "sows." A separate furnace operation is used to form "alloy pig" from the pure aluminum by the addition of alloying elements and this metal is cast into ingots for further processing (ref. 4.1).

For the 6061 alloy, the major alloying elements are magnesium and silicon with smaller additions of chromium and copper. Generally, this phase of production practice involves the carefully controlled melting, alloying, and casting of large 20,000-to 50,000-pound ingots ($\approx$ 9,700 to 21,700 kg). After the ingots are scalped and preheated in vertical electric soaking pits, they are ready for further processing to a particular form of product.

4.2 Manufacture of Wrought Products

4.21 Bar and rod are normally produced by hot rolling or extruding. Cold finished bar and rod are produced by hot working to a size slightly larger than specified and reducing to final dimensions by cold working. A better surface finish and closer dimensional tolerances are obtained in this manner (ref. 4.2).

4.22 A similar process is used to produce rolled structural shapes; special rolls are required. Finishing operations include roller or strech straightening, and heat treatment.

4.23 Roll form shapes are produced by passing strip through a series of roller dies. Each successive pair of rolls cause the work to assume a cross-section shape more nearly approaching that desired. The final desired shape is produced at the last pair of rolls.

4.24 Plate is produced by hot rolling of ingots to slabs (approximately 60-percent reduction), usually in a 4-high reversible mill. The slabs are then further reduced 50 percent in a reversible 2-high mill. The last stage of hot rolling is done in a hot-reversing mill, where the plate is progressively rolled to the final hot mill dimensions. Plate may be subjected to "stress relief" stretching (about 2-percent permanent set) to improve flatness and reduce warpage upon machining. It is then sheared or sawed to the required dimensions (ref. 4.2).

4.25 Sheet is usually produced from plate by cold rolling to final sheet thickness, followed by trimming, tempering, heat treating, stretching, and other finishing operations. Alclad sheet and plate are made by cladding bare material with aluminum alloy 7072 (see Chapter 3, Section 3.111).

4.26 Wire is produced by drawing rod through a series of progressively smaller dies to obtain the desired dimensions.

4.27 Extrusions are produced by subjecting reheated cast billets to enough pressure to force the metal to flow through a die orifice, forming a product whose cross-section shape and size conforms to that of the orifice. Speeds, pressures, and temperatures must be closely controlled to insure uniform quality of extruded products.

4.28 Tube is produced by extruding, by drawing, or by welding. Extruded tube is forced through an orifice as described in 4.27. A die and mandrel are used. Drawn tube is manufactured by a cold process which is similar to drawing bar and rod. A mandrel is used with one end fixed and a bulb attached to the other end. The tube is drawn over the mandrel bulb and through a die at the same time. Welded tube is produced by slitting coil stock into strips and passing the strips through a series of rolls to form tube. The longitudinal seam is welded as the tube leaves the last roll forming station.

4.29 Forgings are made by pressing (press forging) or hammering (drop forging). Relatively heavy equipment is required since aluminum is not as plastic at its forging temperature as steel. Aluminum forgings compare favorably with structural steel in unit strength at about one-third the weight. With comparable strength and with a lower elastic modulus, aluminum alloys have a much higher impact-energy-absorbing capacity than mild steel.

4.3 Available Tempers (ref. 4.4)

4.31 Aluminum alloy 6061 products are available from producers of the alloy in the following tempers:

- F - As fabricated. Applies to products which acquire some temper from shaping processes not having special control over the amount of strain hardening or thermal treatment. For wrought products, there are no mechanical property limits.
- O - Annealed (recrystallized). Applies to the softest temper of wrought products.
- T4 - Solution heat treated and naturally aged to a substantially stable condition. (Designated T42 if performed by user.)
- T6 - Solution treated and artificially aged. (Designated as T62 if performed by user.)

T451 - and T651 — Stress relieve material by streching the following amounts of permanent set after solution treatment:

Plate	1.5 to 3%
Rod, bar, shapes, extruded tube	1.0 to 3%
Drawn tube	0.5 to 3%

Applies directly to plate, rolled or cold-finished rod and bar, and drawn tube. These products receive no further straightening after stretching. T451 products are naturally aged after stretching and T651 products are artificially aged after stretching.

H12 - Strain hardened to 1/4 hard condition to obtain desired mechanical properties with no supplementary thermal treatment. Applies to sheet products.

H13 - Strain hardened to a condition midway between 1/4 and 1/2 hard conditions to obtain desired properties without supplementary thermal treatment. Applies to rod and rivet wire.

T9 - Solution heat treated, artificially aged, and then cold worked to improve strength. Applies to wire products.

4.4 Casting of Alloy Ingots

4.41 Metal for wrought products is alloyed in large 10- to 25-ton double hearth furnaces, carefully controlled and instrumented. The direct chill (DC) method is generally used for casting these ingots. Molten metal is poured into a mold and a hydraulic piston descends slowly as the metal solidifies. Water is sprayed on the outside of the mold to promote rapid solidification. Additional processing may include scalping (machining of outside surfaces) or homogenizing (refs. 4.2, 4.3).

Chapter 4 - References

4.1 Kaiser Aluminum and Chemical Sales, Inc., "Kaiser Aluminum Sheet and Plate Product Information," Second Edition, January 1958.

4.2 Reynolds Metals Co., "The Aluminum Data Book, Aluminum Alloys and Mill Products," 1958.

4.3 Aluminum Co. of America, "Alcoa Aluminum Handbook," 1962.

4.4 The Aluminum Association, Aluminum Standards & Data: 1970-71, New York.

Chapter 5

MANUFACTURING PRACTICES

5.1 General. This heat-treatable aluminum alloy is one of the silicon and magnesium series which combines medium strength, good resistance to corrosion, good weldability, and low cost (ref. 5.3). Available in the bare and Alclad conditions, it is used in heavy-duty structures where resistance to corrosion is essential, i.e., in marine, railroad car, furniture, and pipeline applications, and for aircraft landing mats, pontoon boats, etc.

It is produced in all wrought forms and is often used for service at elevated temperatures in the form of extrusions, tubular products, or forgings. In aerospace flight vehicles, 6061 has been used for storage and handling equipment for red and white fuming nitric acids (common oxidizers for rocket motors). For commercial transports, water storage tanks are often made of Alclad 6061 because of the improved resistance to corrosion compared with bare 6061 (ref. 5.6).

5.2 Forming

5.21 Sheet and plate. The formability of 6061 relative to other aluminum alloys (see table 5.21) is excellent; not only does it have the usual formability of heat-treatable alloys in the O condition, but it also is adaptable to rather severe forming operations in the T4 temper (ref. 5.4).

5.211 Cold forming. The formability of alloy 6061 sheet and plate is directly related to the temper, strength, and ductility. As with other aluminum alloys, high elongation as well as considerable spread between yield and ultimate strength will be indicative of good formability. In the annealed state, the forming quality is similar to 1100-O and 3003-O; in the heat-treated and heat-treated plus aged tempers it forms more nearly like 1100 in the hard temper (ref. 5.5). The simplest and most widely used forming method is probably that of bending. The ease of bending is indicative of most forming operations. Table 5.211 indicates the ease of forming in terms of recommended minimum bend radii, as a function of temper and sheet and plate thickness, using typical mechanical properties of 0.100-inch 2.54-mm) sheet. In general, severe forming and drawing operations should be done with annealed stock and with clean tools free of scratches. T6 properties can be obtained in parts formed in the T4 temper by artificial aging after forming. The T4 temper is obtained by solution treatment at 970° F (521° C) followed by a water quench. Forming is rather easily performed on material in this temper. Reheating to 320° F (160° C) for 16 to 20 hours, or for a lesser time of 6 to 10 hours at 350° F (177° C) produces the T6 temper.

Aluminum sheets are normally formed using operations such as:

Bending	Stamping
Flanging	Spinning
Rolling	Contour Forming
Drawing	Bulging and Expanding
Pressing	Beading and Roll Flanging
Stretching	Necking
Embossing	Curling
Coining.	

The factors influencing the bending of 6061 sheet, as described priorly, also influence the fourteen other forming operations in the same general manner. Because of the lower modulus of elasticity of aluminum compared with steel, a much greater "springback" is expected and is encountered. Over-forming is the common way of correcting the tendency. In addition, reducing the bend radius, increasing the sheet thickness, forming at elevated temperatures, and increasing the total amount of plastic deformation will decrease the extent of springback. Alloy 6061 sheets can be formed to many shapes by drawing; this is the most extensively employed mass production method. Depending upon the desired shape, the part may be produced in one draw or in some cases the reduction is accomplished in successive draws using intermediate annealing to avoid exhausting the ductility and introducing cracks. Deep draws normally employ male and female metal dies. Forming in rubber (Guerin process) for relatively shallow parts is a method where several thin layers of rubber are confined in a pad holder or retainer made of steel or cast iron. A descending ram on which this holder is mounted causes the aluminum sheet to be compressed against a form block to make the required part. If the aluminum is made to flow against a female die using fluid pressures behind a rubber diaphragm, the method is known as "hydroforming." Spinning and high-energy-rate methods have also been successful (ref. 5.16).

Alloy 6061 has been used for fairly recent applications such as in the cold plates for the Saturn launch vehicle and the lunar landing module (LEM). Refrigeration ducts and engine nacelle frames have also been formed from the alloy, producing parts which have been very thin compared to the surface area (ref. 5.7). Upon conventional heat-treatment by quenching from above 900° F (482° C) into cold water, severe distortion may be encountered in thin sections. The usual approach is to straighten or correct parts afterward, which normally is possible. However, there are instances in which parts must be scrapped because they are beyond correction. By utilizing liquid nitrogen as a quenching medium, the distortion is minimized and many hours of process time are eliminated.

5.212 Hot forming. When it is difficult to form heat-treated 6061 alloy by conventional methods, hot forming may be used. Maximum recommended reheating periods are shown in table 5.212. Lesser heat treatment times may give satisfactory results. Although formability at higher temperatures is easier, excessive heating should not be used because of strength loss.

5.22 Shapes, tubes, and pipes. Either extrusion or rolling can be used to produce aluminum shapes. The standard shapes are I-beams, H-beams, channels, angles, tees, and zees. The relative formability of alloy 6061 as tubes or extrusions is essentially the same as that of sheet or plate (table 5.22). As pointed out in section 5.21, better formability can be obtained in the softer tempers with the same precautions as noted. Sections in the O temper are bent and formed more easily than those in the T4 and T6 heat-treated tempers, the latter being the most difficult.

Stretching, wiping, or rolling are general methods used to form shapes and tubes. Sheets, shapes, and tubes are stretch formed by clamping at one end and pulling or stretching over a single male die so as to exceed the elastic limit. The metal section takes the shape of the die by stretching more in the heavier curvature areas than in the shallower ones. When working exceptionally-thin-wall round, square, or rectangular tube on small radii, it is necessary to add a wiper and a flexible mandrel to provide extra support for the tube at the point of bending. Rolls can also be used for the forming, using dies to form the contours.

Shapes are also formed by impact (refs. 5.13, 5.14), which involves driving down a powerful punch onto a slug of aluminum in a die. Part of the aluminum flows plastically through designed orifices; the remainder, between punch and die bottom, is impacted. The process combines the advantages of both forging and extruding. A design manual for impacts is available (ref. 5.14).

5.23 Forging. Alloy 6061 is the most versatile of the heat-treatable aluminum alloys. It can be forged without difficulty and is the most resistant to atmospheric and chemical corrosion of any of the aluminum forging alloys (ref. 5.8). The yield strength of 6061-T6 is almost as high as that of 2024-T4. Machinability and strength-to-weight ratio are fair. Strength at room temperature is moderate. Forgings are made using either the open die or closed die methods and by impact or pressure. Prototype or other few-of-a-kind needs for aluminum parts usually do not warrant the cost of forging dies. Small runs are made using the hand forging open die techniques where the heated stock is worked between flat or simple dies that impose little or no laterial confinement on the material. Hand forgings over a ton in weight can be made in the various tempers defined in table 5.231.

As in all forgings, there is grain flow in 6061 which is characteristic of the forging process. The resultant grain pattern results in anisotropy of properties which must be considered since mechanical properties are a function of the forging direction as well as the size of the hand forging. The process for most production forgings starts with the stock which can vary from 3/8-inch to 4-inch (0.952-10.16 cm) square stock, and rectangles from 3/8 inch (0.952 cm) for the minimum dimension to as much as 10 inches (25.4 cm) on the maximum dimension. Conditioning to remove localized surface defects is permitted at this point.

Forging stock is carefully heated in the range of 600° to 900° F (316° to 482° C). The relative forgeability of 6061, as a function of the forging temperature relative to other aluminum alloys, can be seen in figure 5.232. The excellence of this alloy for forging is to be noted. For example, oil-tank shells for aircraft were forged with a drop hammer from 5052-O alloy; a 60-percent rejection rate for these parts, encountered with 5052-O, was reduced to 20 percent by changing the part to 6061-O (ref. 5.6). Large production runs are made using closed dies. Either drop forging or press forging machinery is used. After preheating, the stock is formed in one step or, in the case of complicated parts, in several operations which may involve reheating. Dies in the forging operation are heated with auxiliary gas or electric heaters. The flash resulting from excess metal over-filling the mold is removed by hot or cold trimming, sawing, or grinding.

Holes in the forging are pressed to produce "punchouts" in the forging. Sometimes the punchout is combined with the trim operation. Very close tolerances can be met in a standard forging by die coining (cold) to precise dimensions, usually within a few thousandths of an inch (25/1000 of mm).

Straightening after heat treatment is often a required operation. Templates combined with indicators and other gages are used to determine the out-of-tolerances. Straightening ranges from hand straightening to "cold restrike" operations. The forgings are inspected for grain flow, mechanical properties, dimensions, and ultrasonic soundness. A design manual for forgings is available from the Aluminum Association of America (ref. 5.12).

5.3 <u>Machining</u>

5.31 Conventional machining. Aluminum alloy 6061 is readily machined in all conventioanl machining operations. The highest machinability is obtained in the hardest temper. In the softer tempers, the alloy tends to be somewhat gummy and is not as machinable. Hand forgings of 6061 which require a large amount of metal removal by roughing out before heat treatment should be machined in the F temper. In those cases where hand forgings are to be machined to very close dimensions with the additional requirement for a good surface condition, the T4 temper yields optimum results. Small hand forgings can be machined successfully in the T6 temper.

It is difficult to produce a precise tabulation of machining parameters for each of the different types of operations. However, table 5.31 is a compilation of typical factors for many common machining operations (ref. 5.9). For grinding, a wheel speed of 6000 ft/min (1800 m/min) is generally used. The downfeed will produce a rough finish if it is kept to about 0.001 inch (0.025 mm) per pass. A fine finish will be produced if the downfeed is kept to a maximum of 0.0005 inch (0.0127 mm) per pass. The crossfeed is approximately 1/3 of the wheel width. Wheel type is A46KV with a water-base emulsion or chemical solution for the grinding fluid.

5.32 Electrochemical and Chemical Machining. Electrochemical and chemical machining have many potential advantages over conventional machining methods. These techniques are considered for the machining of complex-shaped parts where conventional machining techniques may prove to be too difficult or expensive.

5.321 Electrochemical milling. Electrochemical machining for metal shaping subjects the chemically erodible workpiece to the action of anodic current flow in a suitable electrolyte. A second electrode, which is the tool, is provided for the cathodic action. The basic principles are the same as those generalized in Faraday's Law of Electrolysis. However, the electrochemical machining, or ECM, process is the reverse of electrodeposition. An exception is that the cathodic process involves the evolution of hydrogen in most cases, rather than the electrodeposition of a metal. There are a number of tool workpiece configurations that may be employed in the ECM process depending upon the particular type of metal removal geometry desired. It is normally required that fresh electrolyte is supplied to the workpiece. Alloy 6061 is essentially pure aluminum as far as the rate of the electrochemical process is concerned. From the Faraday laws, it can be shown that 1.26 in^3 (20.7 cm^3) of the metal can be removed per minute at 100,000 amperes (assuming 100% efficiency). In practice, efficiencies of 80 to 90 percent are encountered. An electrolyte of 5- to 10-percent NaCl solution has been found to yield excellent results and the process can be carried out using voltages of 10-15 volts. The milling rate of the ECM process depends upon the current capacity of the power supply and the ability of the electrolyte system to provide fresh electrolyte. High electrolyte pressure requirements of 100-250 psi (0.07-0.18 kg/mm^2) provide even electrolyte flow and satisfactory cutting conditions. Temperatures of about 120°F (49°C) produce good quality finishes.

5.322 <u>Chemical milling</u>. The removal of metal stock by chemical dissolution or "chem-milling" in general has also many potential advantages over conventional milling methods. The removal of metal by dissolving in an alkaline or acid solution is now routine for specialized operations on aluminum (ref. 5.6). For flat parts, where large areas having complex or wavy peripheral outlines are to be reduced only slightly in thickness, chemical milling is usually the most economical method. It is basically a three-step process (ref. 5.10): A maskant is applied to protect surface areas that will not be milled. The metal is immersed in an etching bath which may be acidic or basic to remove metal from specific areas so as to produce the desired configuration. Finally, the maskant is stripped from the part. To produce a simple shape, the masking and milling procedure is only performed once. Complex designs are usually produced by repeating the masking and milling sequence until the desired shape is achieved.

Standard mechanical property tests indicate that chemical milling has no appreciable effect on the compression, tension, or shear properties of aluminum alloy 6061 (ref. 5.11). Fatigue tests of 6061-T4 show that chemical milling does not significantly affect the fatigue life of the alloy. Alloy 6061 can be chemically milled in all forms and in the O, T4, T6, or T62 conditions.

TABLE 5.21. — Relative Formability of Heat-Treatable Aluminum Alloys

Source	Ref. 5.2
Order of Decreasing Formability	
1) No. 21 and No. 22 Brazing Sheet 2) 6061 3) 6066	4) 2024 5) 2014 6) 7075 7) 7178

TABLE 5.211. — Approximate Bend Radii for 90 Degree Cold Bend (a)

Source	Ref. 5.1							
	Thickness, t, inches (c)							
Temper	1/64	1/32	1/16	1/8	3/16	1/4	3/8	1/2
O	0	0	0	0	0-1t	0-1t	1/2t-2t	1t-21/2t
T4 (b)	0-1t	0-1t	1/2t-11/2t	1t-2t	11/2t-3t	2t-4t	21/2t-4t	3t-5t
T6 (b)	0-1t	1/2-11/2t	1t-2t	11/2t-3t	2t-4t	3t-4t	31/2t-51/2t	4t-6t

(a) Radii for various thickness expressed in terms of thickness, t

(b) Alclad sheet can be bent over slightly smaller radii than the corresponding tempers of the uncoated alloy

(c) 1 inch = 25.4 mm

TABLE 5.212. – Recommended Maximum Holding Times for 6061-T6 Alloy Prior to Forming, as a Function of Holding Temperature

Source	Ref. 5.4	
Temperature of Hold °F	°C	Time in Indicated Units
300	149	100-200 hours
325	163	50-100 hours
350	177	8-10 hours
375	191	1-2 hours
400	204	30 minutes
425	218	15 minutes
450	232	5 minutes
500	260	No

Note: The above guide indicates maximum heating periods; it should be understood that in many instances, shorter heating times will give satisfactory results.

TABLE 5.231. – Heat-Treat Tempers for Hand Forgings

Source	Ref. 5.8
Temper	Treatment
F	As forged, no thermal treatment following fabrication operation
W	Solution heat-treated and quenched in water at 140° F (60° C)
T4	Solution heat-treated, quenched in water at 140° F (60° C) and naturally aged to a substantially stable condition
T41	Solution heat-treated, quenched in water at 212° F (100° C) and naturally aged to a substantially stable condition
T6	Solution heat-treated, quenched in water at 140° F (60° C) and artificially aged
T62	Solution heat-treated, quenched in water at 140° F (60° C), stress relieved by cold compression, artificially aged

TABLE 5.31. — Machining Recommendations for Solution Treated and Aged 6061 Alloy

Source	Ref. 5.7						
		High Speed Tool			Carbide Tool		
Operation	Cutting Conditions*	Speed fpm	Feed ipm	Tool Mat'l	Speed fpm	Feed ipm	Tool Mat'l
Single point turning	0.250 inch depth of cut	600	0.015	T1, M1	1100	0.015	C-1
	0.050 inch depth of cut	800	0.008	T1, M1	1400	0.008	C-2
Form tool, turning	0.500 inch form tool width	450	0.0035	T1, M1	1000	0.0035	C-2
	0.750 inch form tool width	450	0.0035	HSS	1000	0.003	C-2
	1.000 inch form tool width	450	0.003	HSS	1000	0.003	C-2
	1.500 inch form tool width	450	0.0025	HSS	1000	0.002	C-2
	2.000 inch form tool width	450	0.002	HSS	1000	0.002	C-2
Boring	0.010 inch depth of cut	600	0.008	T1, M1	1000	0.010	C-1, C-3
	0.050 inch depth of cut	570	0.010	HSS	1050	0.015	C-1, C-3
	0.100 inch depth of cut	540	0.015	HSS	1000	0.020	C1-C-3
Planing	0.500 inch depth of cut	300	0.060	T1, M1	300	0.060*	C-, C-3
	0.050 inch depth of cut	300	0.050	T1, M1	300	0.050	C-2
	0.010 inch depth of cut	300	3/4**	T1, M1	300	3/4**	C-2
Face milling	0.250 inch depth of cut	800	0.020*	T1, M1	max	0.018*	C-2
	0.050 inch depth of cut	1000	0.022*	T1, M1	max	0.020*	C-2
End milling (profiling)	3/4 inch cutter diameter	700	0.006*	M1, M10	1200	0.005*	C-2
	1/2 inch cutter diameter	700	0.009*	M1, M10	1200	0.008*	C-2
	1/8 inch cutter diameter	1000	0.0007*	M1, M10	1800	0.0005*	C-2
	3/8 inch cutter diameter	1000	0.005*	M1, M10	1800	0.004*	C-2
	3/4 inch cutter diameter	1000	0.007*	M1, M10	1800	0.006*	C-2
	1 to 2 inch cutter diameter	1000	0.010*	M1, M10	1800	0.009*	C-2
Drilling	1/8 inch nominal hole diameter	250	0.003	M1, M10			
	1/4 inch nominal hole diameter	250	0.007	HSS			
	1/2 inch nominal hole diameter	250	0.012	HSS			
	3/4 inch nominal hole diameter	250	0.016	HSS			
	1 inch nominal hole diameter	250	0.020	HSS			
	1 1/2 inch nominal hole diameter	250	0.025	HSS			
	2 inch nominal hole diameter	250	0.030	HSS			
	3 inch nominal hole diameter	250	0.030	HSS			

* Feed - inches per tooth
Note: 1 inch = 25.4 mm.

** Feed - 3/4 the width of square nose finishing tool

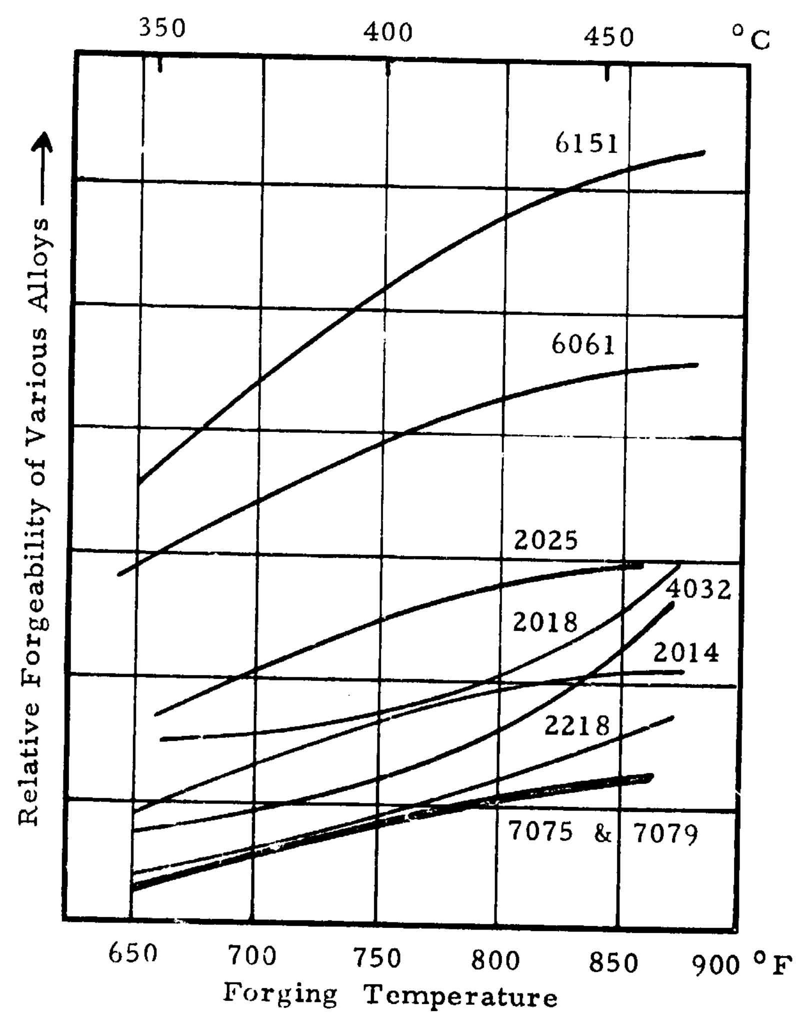


FIGURE 5.232. – Relative forgeability of various aluminum alloys.

(Ref. 5.8)

Chapter 5 - References

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Chapter 6

SPACE ENVIRONMENT EFFECTS

6.1 General. Aluminum alloys have been used in both structural and nonstructural applications in launch vehicles and spacecraft with excellent success since, in general, the aluminum alloys are relatively insensitive to degradation in typical space environment conditions. The vapor pressures of the structural aluminum alloys are sufficiently high (table 6.1) so that the combined temperature—vacuum effects generally are negligible. Structural alloys such as 6061 are sufficiently hardened so that nuclear and space indigenous radiation induced defects do not significantly affect mechanical and physical properties, at room ambient and elevated temperatures, below accumulated doses of about 10^{22} particles/cm^2. When irradiated at cryogenic temperatures, the threshold may be lowered one or two decades, but the probabilities of experiencing doses on this order of magnitude are extremely remote except in the vicinity of nuclear reactors.

Elevated temperatures, hard vacuums, high energy radiations, and micrometeoroids can singularly and collectively influence surface characteristics of 6061 by desorption processes and erosion. These phenomena might be of great importance if optical properties, lubrication, certain electrical properties, etc., were critical design parameters.

Sputtering of the surface by atomic or molecular particles can deteriorate surface finishes in a relatively short period. A 300-Å coating of aluminum (10^{-5} g/cm^2) can be destroyed in one month during a period of low intensity solar wind or in several hours during a solar storm, for example. The threshold energies of particles required to remove one or more atoms of the surface material they impinge are quite low, of the order of 6, 11, and 12 eV for O, N_2 and O_2 particles, respectively. Estimates of surface erosion by sputtering are given in table 6.2 for aluminum alloys.

Micrometeoroids can produce surface erosion similar to sputtering, although perhaps on a more macroscopic scale, as well as punctures. Micrometeoroids vary widely in mass, composition, velocity, and flux; generalizations about the rates of erosion and penetration, therefore, must be used with care. The predicted and measured frequency of impact as a function of meteoroid mass is given in figure 6.1. Data are given in figures 6.2 and 6.3 on the penetration and cratering of aluminum alloy skins of various thicknesses. Calculations of armor thickness required for protection of different structures and orientations are given in table 6.3. The design of bumper-hull meteoroid protection systems is discussed in reference 6.12.

The surface erosion of aluminum alloys due to corpuscular radiation is probably insignificant, amounting to something of the order of 254 nanometers per year. Indigenous space radiation, however, will tend to accelerate the removal of surface films, which might result in loss of lubricity and an increased propensity to "cold weld." The interaction of indigenous radiation with desorption gases might cause some spurious, transient electrical conditions when aluminum alloys are used for electrical applications. The interaction of indigenous radiation with the alloys may produce some internal heating that might be significant for small items and may induce some radioactivity.

TABLE 6.1. – Evaporation Rates in Vacuum of Typical Elements Used in Aerospace Alloys (a, b)

Source	Ref. 6.14				
Element	Evaporation Rate, $g/cm^2/sec$				
	$-100^\circ C$	$0^\circ C$	$100^\circ C$	$250^\circ C$	$500^\circ C$
Aluminum	1.2×10^{-81}	1.1×10^{-49}	2.0×10^{-33}	1.7×10^{-21}	6.5×10^{-12}
Titanium	$<10^{-99}$	$2.5 \times 10^{-}$[illegible]0	4.1×10^{-42}	7.4×10^{-28}	2.0×10^{-16}
Iron	$<10^{-99}$	6.8×10^{-64}	2.4×10^{-44}	4.8×10^{-29}	9.1×10^{-17}
Nickel	$<10^{-99}$	5.7×10^{-70}	$1.$[illegible] $\times 10^{-48}$	6.7×10^{-32}	1.7×10^{-18}
Copper	1.2×10^{-94}	1.4×10^{-56}	6.2×10^{-39}	4.0×10^{-25}	4.7×10^{-14}
Chromium	9.5×10^{-92}	1.0×10^{-54}	1.4×10^{-37}	3.8×10^{-24}	2.2×10^{-13}
Vanadium	$<10^{-99}$	1.9×10^{-87}	2.1×10^{-61}	5.0×10^{-41}	1.2×10^{-24}
Manganese	2.2×10^{-72}	1.1×10^{-42}	6.5×10^{-28}	3.8×10^{-18}	1.6×10^{-9}
Silicon	$<10^{-99}$	1.9×10^{-62}	3.6×10^{-43}	4.3×10^{-28}	5.5×10^{-16}
Magnesium	2.9×10^{-36}	5.3×10^{-20}	1.8×10^{-12}	1.3×10^{-6}	6.6×10^{-2}
Zinc	3.5×10^{-30}	5.1×10^{-16}	1.8×10^{-9}	2.3×10^{-4}	2.80

(a) The actual evaporation rate of each element in combination with others will be lower.

(b) The values may be in error by several orders of magnitude as they have been extrapolated from high-temperature data. The rates at low tempeatures will be considerably less than the values given in the table.

TABLE 6.2. —Estimated Rate of Removal and Time to Remove 1×10^{-7} mm of Aluminum by Sputtering

Source	Ref. 6.2			
	Orbiting Vehicle		Escaping Vehicle	
Height, km	Rate, atom cm^{-2} sec^{-1}	Time, sec/1×10^{-7} mm	Rate, atom cm^{-2} sec^{-1}	Time, sec/1×10^{-7} mm
100	3.1×10^{16}	1.9×10^{-2}	3.4×10^{17}	1.8×10^{-3}
220	2.0×10^{13}	30	2.0×10^{17}	3.0×10^{-3}
700	2.2×10^{9}	2.7×10^{5}	3.4×10^{11}	1.8×10^{3}
2500	4.3×10^{5}	1.4×10^{9}	1.6×10^{8}	3.8×10^{6}

TABLE 6.3. —Computed Thicknesses of Armor Required for Protection from Meteoroid Impact over a Period of 1000 Days

Source	Ref. 6.11							
Structure	Orientation (a)	Vulnerable Area ft^2	Vulnerable Area cm^2	Prob'y No Destructive Impact, %	Av. No. of Destructive Impacts per Mission	Critical Thickness in	Critical Thickness cm
Plane	i, leading	1000	92.9	99.5	0.005	0.209	0.530
		500	46.5	99.75	0.0025	0.209	0.530
	i, trailing	1000	92.9	99.5	0.005	0.109	0.278
		500	46.5	99.75	0.0025	0.109	0.278
	j, either side alone	2000	185.8	99.0	0.01	0.232	0.590
		1000	92.9	99.5	0.005	0.232	0.590
	k, either side alone	2000	185.8	99.0	0.01	0.197	0.500
		1000	92.9	99.5	0.005	0.197	0.500
Cylinder	i	2000	185.8	99.0	0.01	0.215	0.547
	j	2000	185.8	99.0	0.01	0.190	0.481
	k	2000	185.8	99.0	0.01	0.205	0.521
Sphere	(random)	2000	185.8	99.0	0.01	0.198	0.502

(a) i = direction of the apex of earth's movement
j = direction within ecliptic plane, approximately away from sun, exactly perpendicular to apex of earth motion
k = direction perpendicular to ecliptic plane, southward

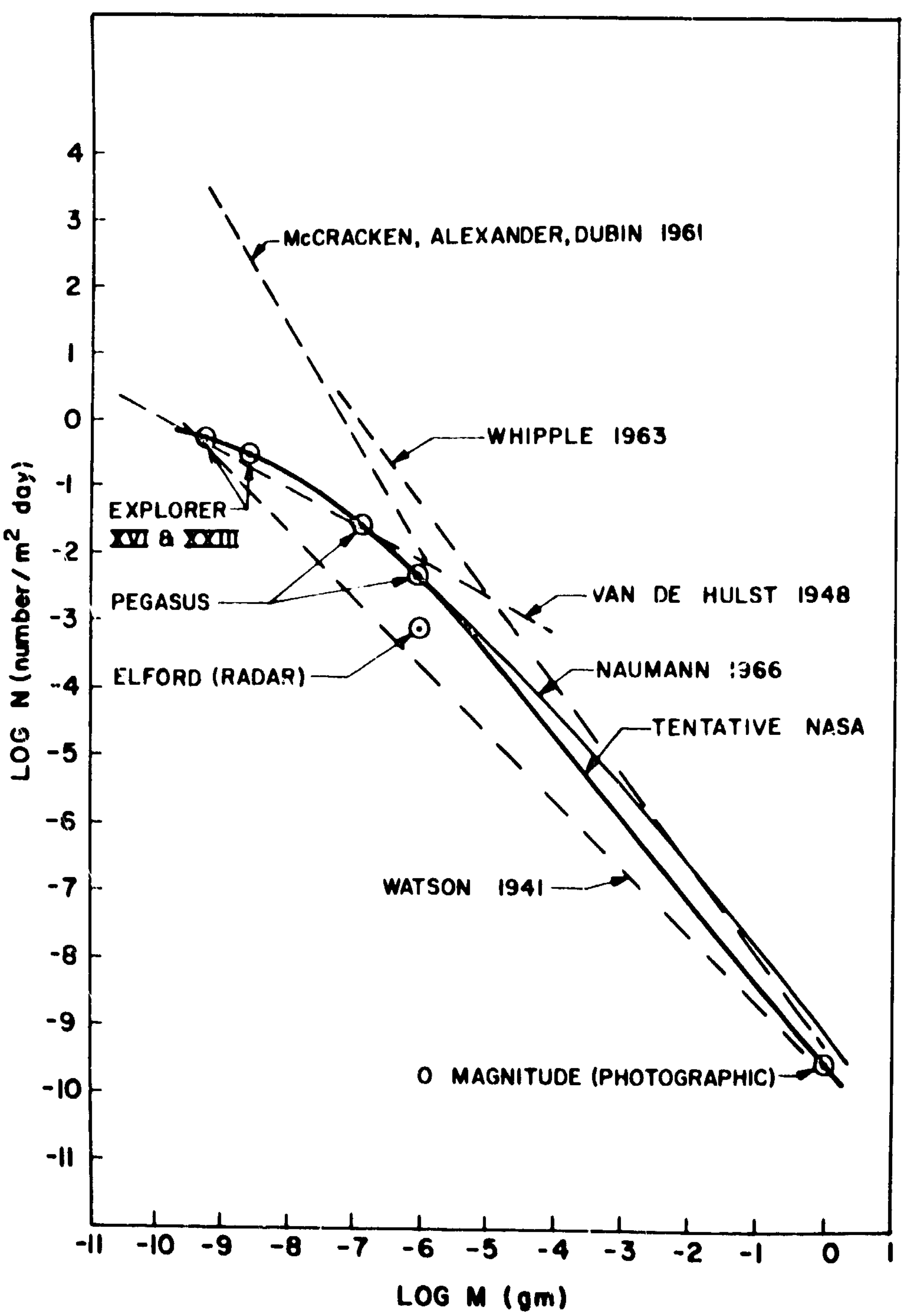

FIGURE 6.1. -- Various estimates of meteoroid mass influx. (Ref. 6.3)

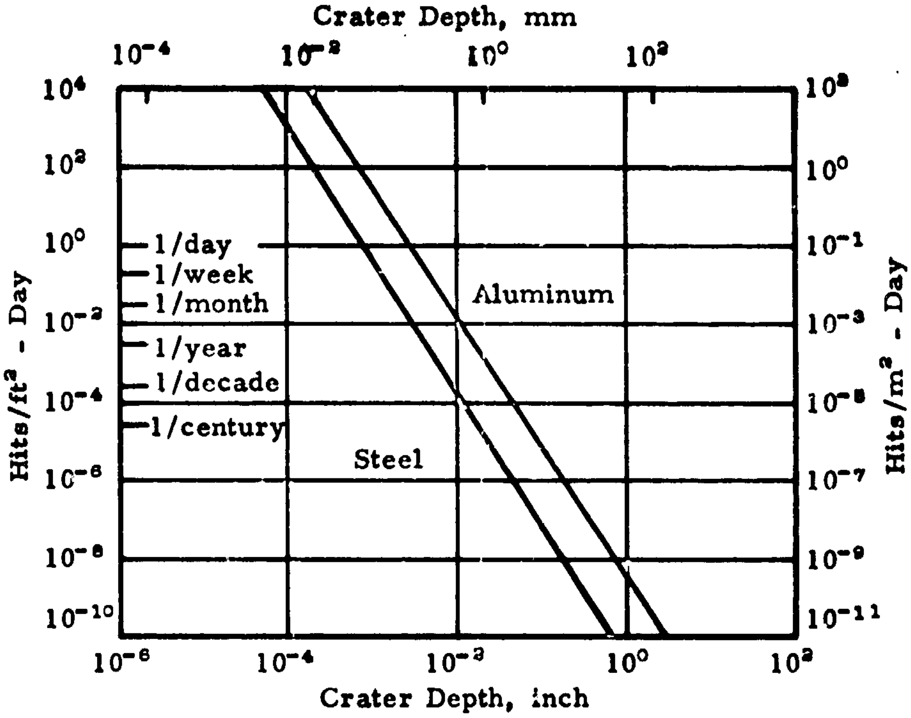

FIGURE 6.2. — Hit rate vs crater depth in the earth neighborhood but without earth shielding.

(Ref. 6.4)

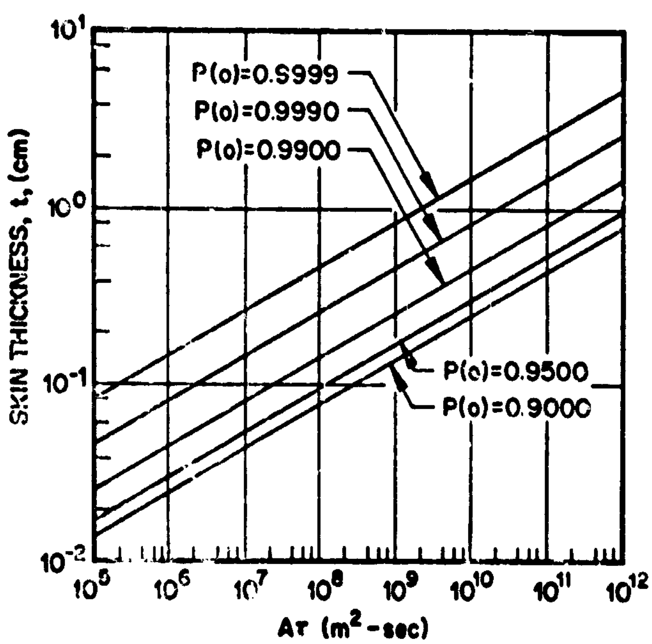

FIGURE 6.3. — Sheet thickness of Al as a function of the surface area–lifetime product required for various probabilities of no meteoroid puncture.

(Ref. 6.1)

Chapter 6 - References

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Chapter 7

STATIC MECHANICAL PROPERTIES

7.1 <u>Specified Properties</u>

7.11 NASA Specified Properties

7.111 NASA specified mechanical properties for die forgings and separately forged test bars, table 7.111.

7.112 NASA specified mechanical properties for hand forgings, table 7.112.

7.12 AMS Specified Properties

7.121 AMS specified properties are given in detail in reference 7.1.

7.13 Military Specified Properties (see table 2.2)

7.14 Federal Specified Properties (see table 2.2)

7.15 ASTM Specified Properties

7.151 ASTM specified properties are given in reference 7.2 (see also table 2.2)

7.16 Aluminum Association Mechanical Property Limits

7.161 Aluminum Association mechanical property limits are given in reference 7.3.

7.2 <u>Elastic Properties and Moduli</u>

7.21 Poisson's ratio, 0.33 (ref. 7.8)

7.22 Young's modulus of elasticity, E

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7.222 Typical value of E, 10.0×10^3 ksi (7.03×10^3 kg/mm^2) (ref. 7.3).

7.223 Effect of temperature on the tensile and compressive moduli (E and E_c, figure 7.223.

7.224 Modulus of elasticity at low temperatures, figure 7.224.

7.23 Compression modulus E_c (see also figure 7.223)

7.231 Design value of E_c, 10.1×10^3 ksi (7.10×10^3 kg/mm^2) (ref. 7.4).

7.24 Modulus of rigidity (shear modulus), G

7.241 Design value of G, 3.8×10^3 ksi (2.67×10^3 kg/mm^2) (ref. 7.4).

7.25 Tangent modulus

7.251 Tangent modulus curves for sheet and plate in T6 condition, figure 7.251.

7.252 Tangent modulus curve for extrusions in T6 condition, figure 7.252.

7.26 Secant modulus

7.27 Bending modulus of rupture for T6 round tubing, figure 7.27

7.28 Torsional modulus of rupture for T6 tubing, figure 7.28.

7.3 <u>Hardness</u>

7.31	Brinell scale (500-kg load)	Condition O	30
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7.32 End-quench hardenability of alloy in solution treated and aged condition, figure 7.32.

7.33 Hardness of T6 bar at cryogenic temperatures, figure 7.33.

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7.4112	Elongation values for sheet, plate and tube, table 7.4112.
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7.4224	Typical compressive stress-strain curves for Clad 6061-T6 at 500° F, figure 7.4224.
7.4225	Typical compressive stress-strain curves for Clad 6061-T6 at 600° F, figure 7.4225.
7.43	Bending

TABLE 7.111. — NASA Specified Mechanical Properties for Die Forgings and Separately Forged Test Bars

Alloy	6061-T6 (b)			
Specification	NASA-MSFC-SPEC-144B			
Max. sect. thickness	4 inches (10.16 cm)			
Orientation	A		B	
F_{tu}, min, ksi (kg/mm^2)	38.0 (a)	(26.7)	38.0	(26.7)
F_{ty}, min, ksi (kg/mm^2)	35.0 (a)	(24.6)	35.0	(24.6)
e(2 in or 4D), min, percent	7		5	

A Test specimen parallel to forging flow lines
B Test specimen not parallel to forging flow lines
(a) Tensile and yield strength test requirements may be waived for material in any direction in which the dimension is less than 2 inches (5.08 cm) because of the difficulty in obtaining a tension test specimen suitable for routine control testing
(b) Die forgings in some configurations of this alloy can be purchased in the heat treated and mechanically stress relieved T652 temper conforming to the mechanical properties requirements specified for the T6 temper.

TABLE 7.1112. — NASA Specified Mechanical Properties for Hand Forgings

Alloy	6061-T6					
Specification	NASA-MSFC-SPEC-144B					
Thickness (b)	Axis of Test Specimen	F_{tu}, min ksi	F_{tu}, min kg/mm^2	F_{ty}, min ksi	F_{ty}, min kg/mm^2	e(2 in or 4D), min, percent
≤ 4.000 in	L	38.0	26.7	35.0	24.6	10
(10.16 cm)	LT	38.0	26.7	35.0	24.6	8
	ST	37.0	26.0	33.0	23.2	5
4.001-8.000 in	L	37.0	26.0	34.0	23.9	8
(10.16-20.32 cm)	LT	37.0	26.0	34.0	23.9	6
	ST	35.0	24.6	32.0	22.5	4

(a) Maximum cross-sectional area is 256 in^2 (0.165 m^2)
(b) Thickness is measured in the short transverse direction and applies to the dimension "as forged," before machining
(c) Tensile property requirements may be waived for directions in which the dimension is less than 2 inches (5.08 cm).

TABLE 7.4111. – Design Mechanical Properties of Sheet, Plate, Rolled Bar, Rod and Shapes, Tube, and Pipe

Alloy	6061								6061		6061 and 6062			
Form	Sheet and plate								Bar, rod, wire and shapes; rolled, drawn or cold-finished		Tube, drawn		Pipe	
Condition	Heat treated T4 or T451				Heat treated and aged T6 or T651				Heat treated T4 or T451	Heat treated and aged T6 or T651	Heat treated T4	Heat treated and aged T6	Heat treated and aged T6	
Thickness, in	0.010–2.000		2.001–3.000		0.010–2.000		2.001–3.000		≤8.000 (c)	≤8.000 (c)	0.025–0.500	0.025–0.500	0.049–0.154	0.065–0.687
Size, in													½–¾	1–12
Basis	A	B	A	B	A	B	A	B	A	A	A	A	A	A
Mechanical properties:														
F_{tu}, ksi:														
L	...	...	...	...	42	43	...	...	30	42	30	42	42	38
LT	30	32	30	32	42	43	42	43	...	...	...	...	...	...
F_{ty}, ksi:														
L	...	...	...	...	36	38	...	...	16	35	16	35	35	35
LT	16	18	16	18	35	37	35	37	...	...	...	...	...	...
F_{cy}, ksi:														
L	...	...	...	...	35	37	...	...	14	34	14	34	34	35
LT	16	18	...	...	36	38	...	...	...	...	...	...	...	...
F_{su}, ksi	20	21	...	...	27	28	...	...	20	27	20	27	27	24
F_{bru}, ksi:														
(e/D=1.5)	48	51	...	...	67	69	...	...	48	67	48	67	67	61
(e/D=2.0)	63	67	...	...	88	90	...	...	63	88	63	88	88	80
F_{bry}, ksi:														
(e/D=1.5)	22	25	...	...	50	53	...	...	22	49	22	49	49	49
(e/D=2.0)	26	29	...	...	56	61	...	...	26	56	26	56	56	56
e, percent:														
L	...	...	...	...	...	...	...	...	18	10	(a)	(a)	12	10
LT	(a)	...	16	...	(a)	...	6	...	...	...	...	...	...	...

(a) Elongation values are in table 7.4112.

(b) 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

(c) Cross-sectional area ≤ 50 in^2 (322.5 cm^2).

(Ref. 7.4)

TABLE 7.4112. – Percent Elongation Values for Sheet, Plate, and Tubing

Condition	Thickness range, inch	Elongation, percent	
T4 or T451 (6061 sheet and plate)..	0.010–0.020	14	
	0.021–0.249	16	
	0.250–1.000	18	
	1.001–2.000	16	
T6 or T651 (6061 sheet and plate)..	0.010–0.020	8	
	0.021–0.499	10	
	0.500–1.000	9	
	1.001–2.000	8	
		Full-section specimen	Cut-out specimen
T4 (6061 and 6062 tube)	0.025–0.049	16	14
	0.050–0.259	18	16
	0.260–0.500	20	18
T6 (6061 and 6062 tube)	0.025–0.049	10	8
	0.050–0.259	12	10
	0.260–0.500	14	12

Note: 1 inch = 25.4 mm.

(Ref. 7.4)

TABLE 7.4113. – Design Mechanical Properties of Forgings

Alloy	MIL-A-22771, Type 6061		
Form	Die forgings	Hand forgings[a]	
Condition	T6 and -T652	T6	
Thickness, in.	≤ 4.000	≤ 4.000	4.001–8.000
Basis	A	A	A
Mechanical properties:			
F_{tu}, ksi			
L	38	38	37
LT	....	38	37
ST	38	37	35
F_{ty}, ksi			
L	35	35	34
LT	....	35	34
ST	35	33	32
F_{cy}, ksi			
L	36	36	35
LT	....	36	35
ST	36	34	33
F_{su}, ksi	25	25	24
F_{bru}, ksi			
(e/D=1.5)	61	61	59
(e/D=2.0)	76	76	74
F_{bry}, ksi			
(e/D=1.5)	54	54	63
(e/D=2.0)	61	61	59
e, per cent			
L	7	10	8
LT	....	8	6
ST	5	5	4

(a) Maximum cross-sectional area 256 in^2 (1651 cm^2).

"For die forgings, the L and ST values for the directions parallel (within ± 15 degrees) and not parallel (as close as possible to the short transverse direction) respectively, to the forging flow lines."

Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

(Ref. 7.4)

TABLE 7.4114. – Design Mechanical Properties of Extruded Rod, Bar, and Shapes

Alloy	QQ-A-200/8 6061										
Form	Extruded Rod, Bar and Shapes										
Condition	T4, T4510 T4511	T6, T6510 and T6511									
Cross-Sectional Area, in.^{2}	≤ 32										
Thickness, in.	≤3	≤0.249		0.250–0.499		0.500–1.000		1.001–2.999		3.000–6.500	
Basis	A	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:											
F_{tu}, ksi											
L	25	38	41	38	41	38	41	38	41	38	41
LT	.....	37	40	37	40	37	40	33	35	33	35
F_{ty}, ksi											
L	16	35	38	35	38	35	38	35	38	35	38
LT	.....	33	36	33	36	33	36	28	31	28	31
F_{cy}, ksi											
L	14	35	38	35	38	35	38	35	38	35	38
LT	.....	35	38	35	38	35	38	30	33	30	33
F_{su}, ksi	16	27	29	27	29	27	29	19	21	19	21
F_{bru}, ksi											
e/D=1.5	42	64	69	64	69	64	69	49	68	49	68
e/D=2.0	55	82	89	82	89	82	89	69	74	69	74
F_{bry}, ksi											
e/D=1.5	22	54	58	54	58	54	58	42	46	42	46
e/D=2.0	26	60	65	60	65	60	65	51	55	51	55
e, percent:											
L	16	8	–	10	–	10	–	10	–	10	–
LT	.....	–	–	–	–	–	–	–	–	–	–

(a) Except for F_{tu}, L and F_{ty}, L, values for these thickness ranges are based on fewer data than recommended in MIL-HDBK-5 Guidelines.
Note: 1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2.

(Ref. 7.4)

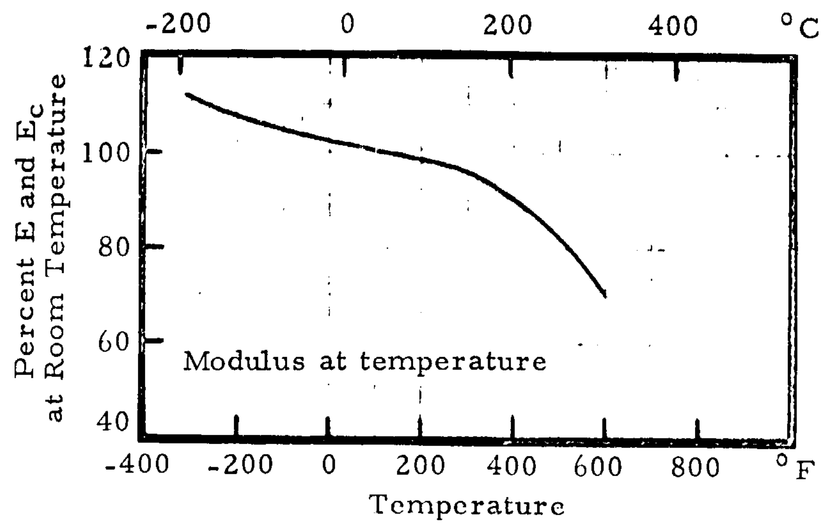

FIGURE 7.223. – Effect of temperature on the tensile and compressive moduli of 6061.

(Ref. 7.4)

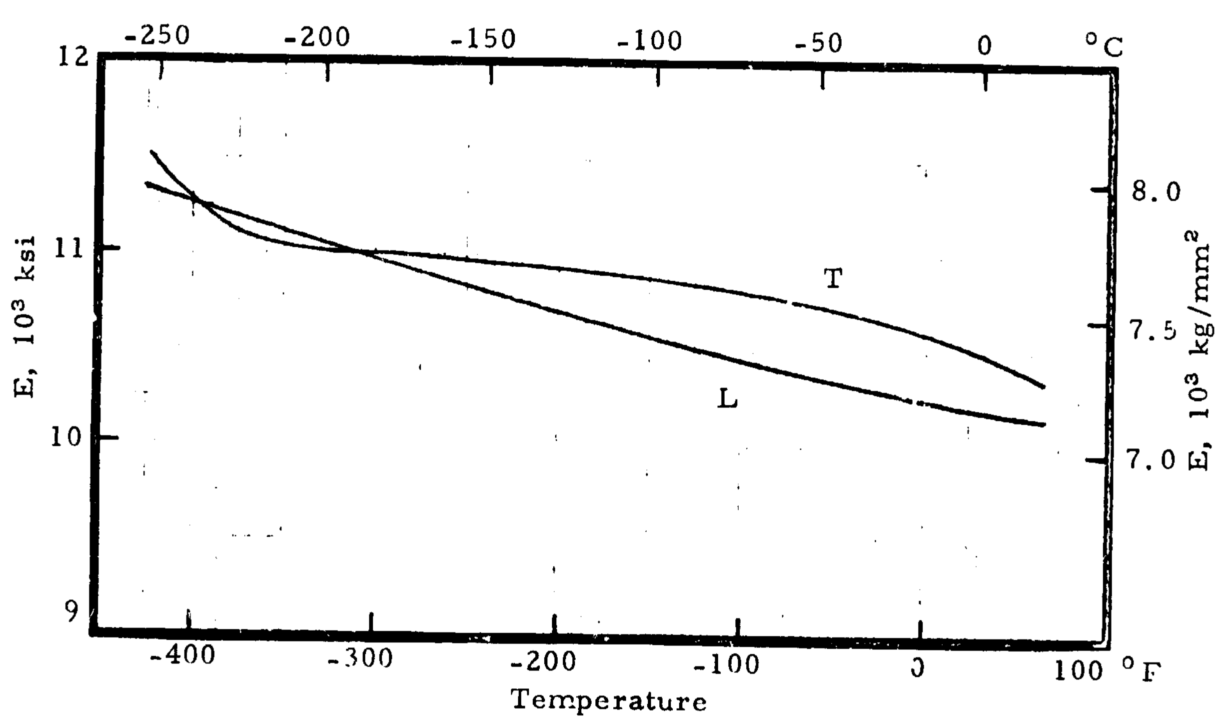

FIGURE 7.224. – Modulus of elasticity of 6061 sheet at low temperatures; thickness, 0.100 in (2.54 mm).

(Ref. 7.9)

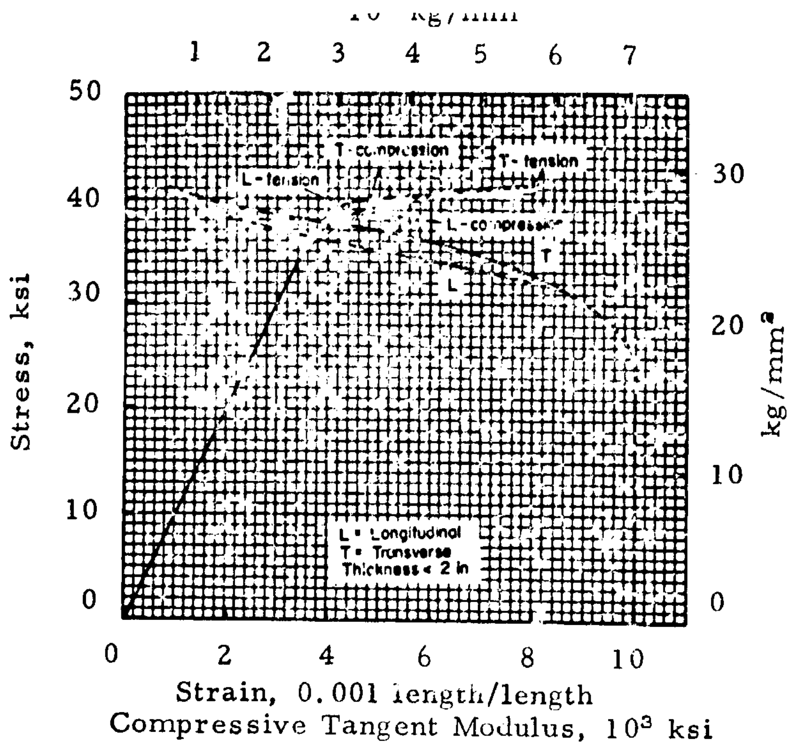

FIGURE 7.251. — Typical stress-strain and tangent-modulus curves for 6061-T6 sheet and plate at room temperature (2 in = 50.8 mm). (Ref. 7.4)

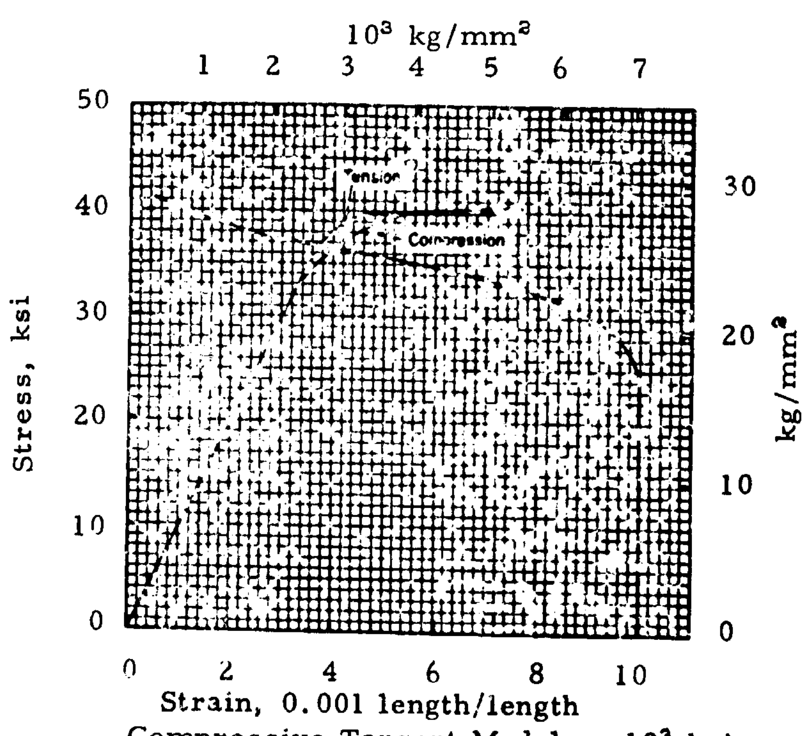

FIGURE 7.252. — Typical stress-strain and tangent-modulus curves for 6061-T6 extrusions at room temperature (longitudinal). (Ref. 7.4)

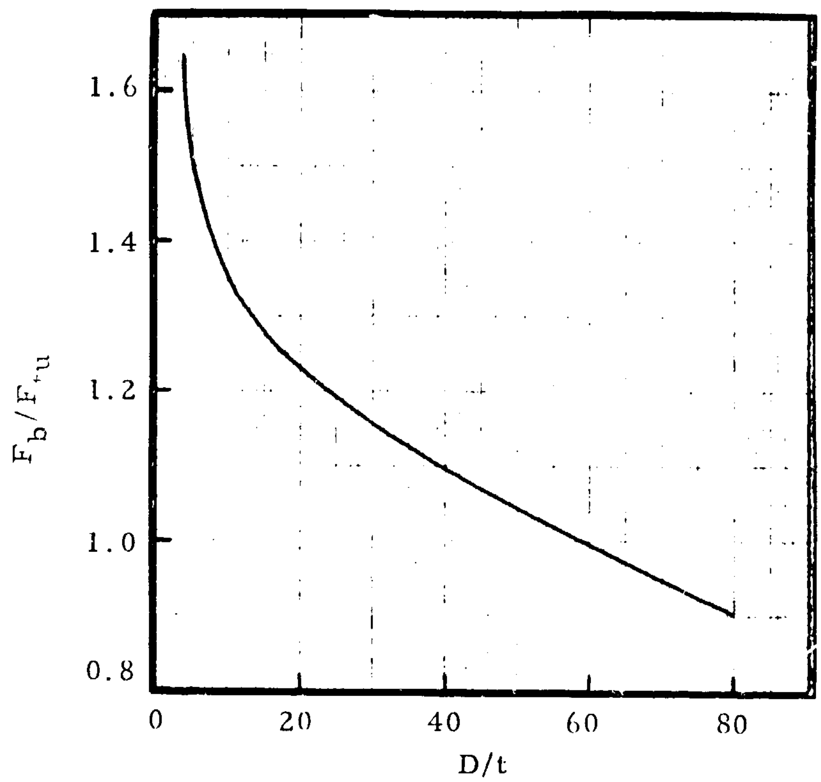

FIGURE 7.27. – Bending modulus of rupture for 6061-T6 round tubing. (Ref. 7.4)

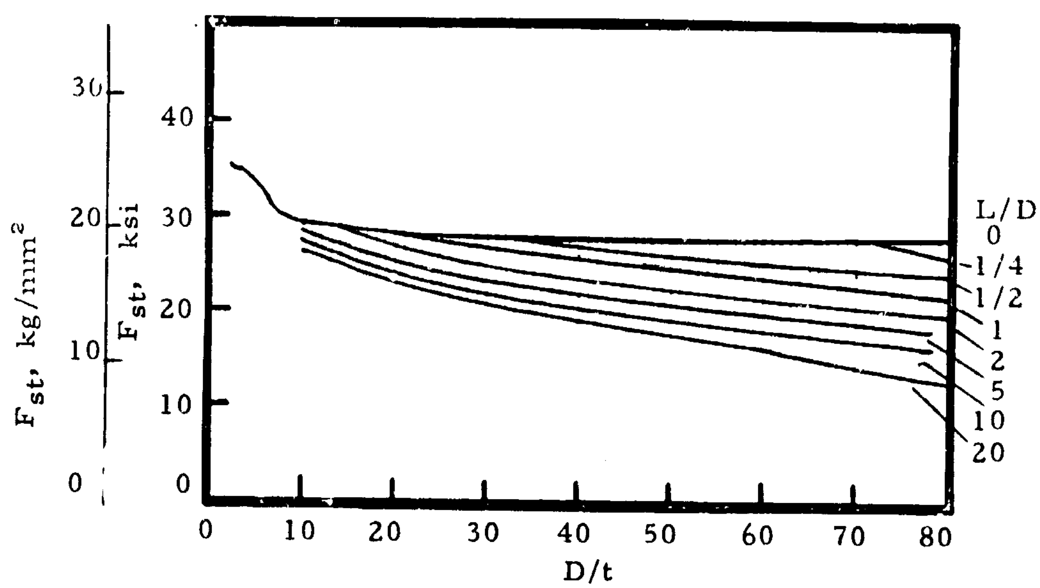

FIGURE 7.28. – Torsional modulus of rupture for 6061-T6 tubing [F_{tu} = 42 ksi (29.5 kg/mm^2)]. (Ref. 7.4)

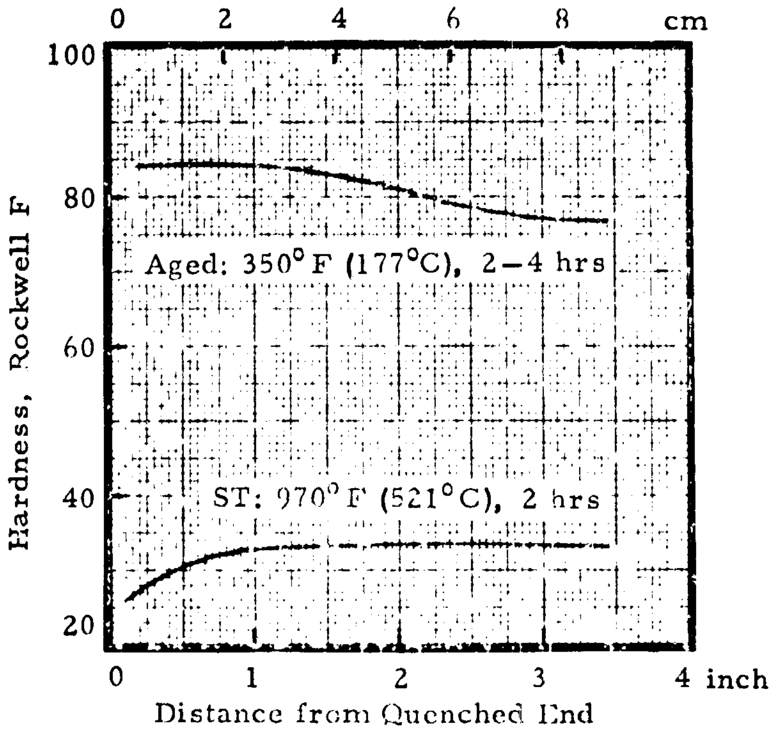

FIGURE 7.32. – End-quench hardenability of 6061 in solution treated and aged conditions.

(Ref. 7.7)

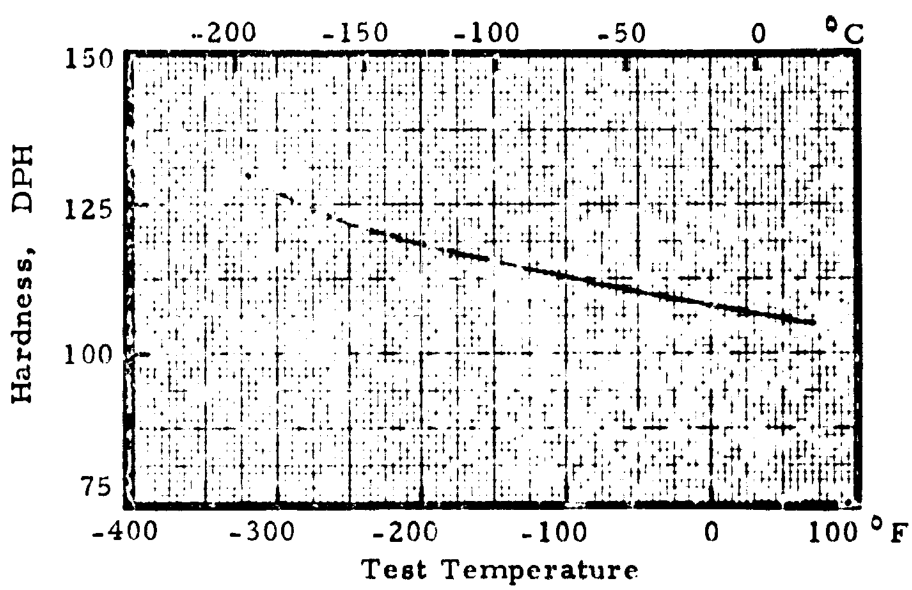

FIGURE 7.33. – Hardness of 6061-T6 bar at cryogenic temperatures; 0.750-in diam (19.1 mm).

(Refs. 7.17, 7.19, 7.20)

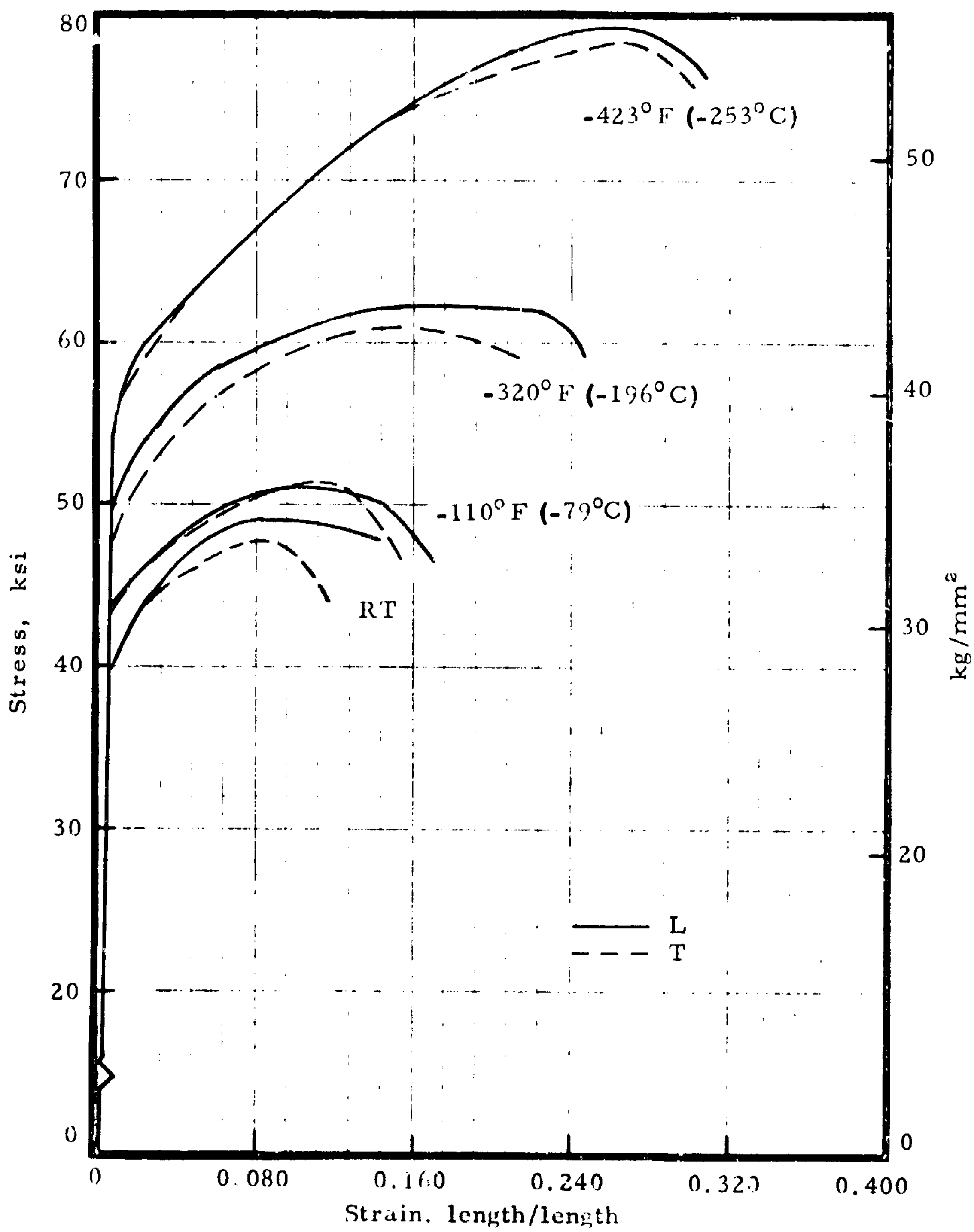

FIGURE 7.4122. – Stress-strain diagram for 6061-T6 sheet at room and low temperature; 0.100-in (2.54-mm).

(Ref. 7.9)

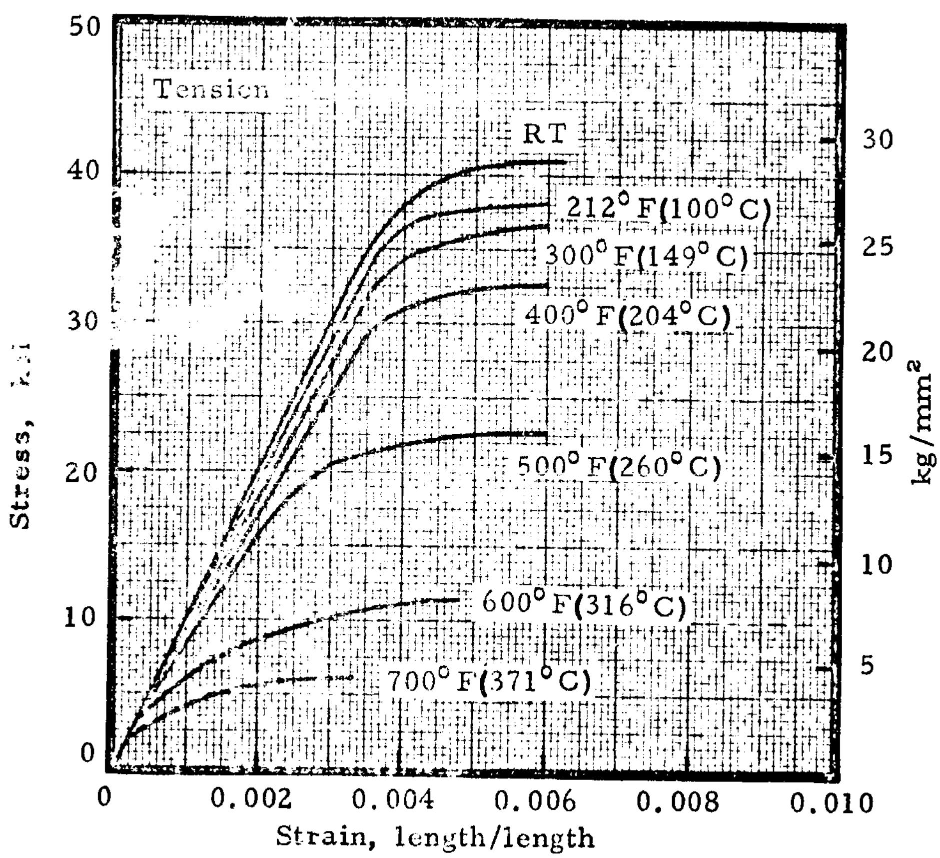

FIGURE 7.4123. — Stress-strain curves for 6061 and 6062 in T-6 condition.

(Ref. 7.8)

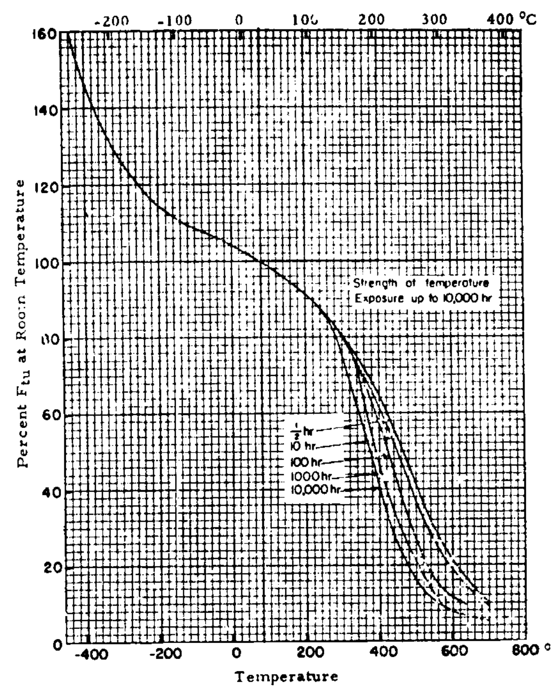

FIGURE 7.4131. – Effect of temperature on the ultimate tensile strength of 6061-T6 (all products).

(Ref. 7.4)

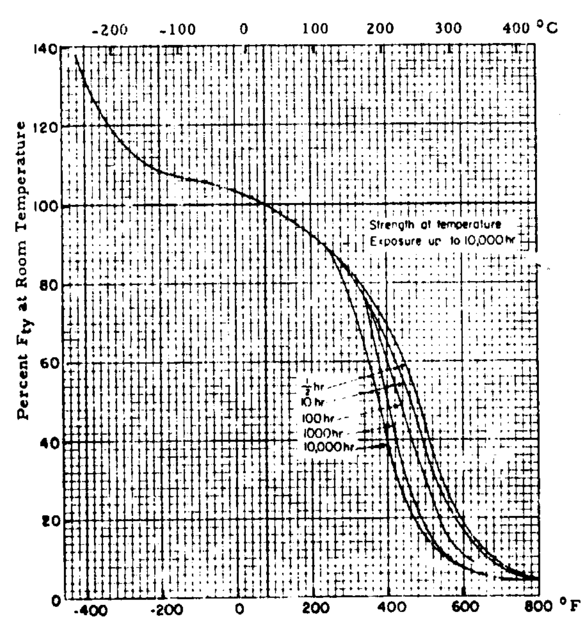

FIGURE 7.4132. – Effect of temperature on the tensile yield strength of 6061-T6 (all products).

(Ref. 7.4)

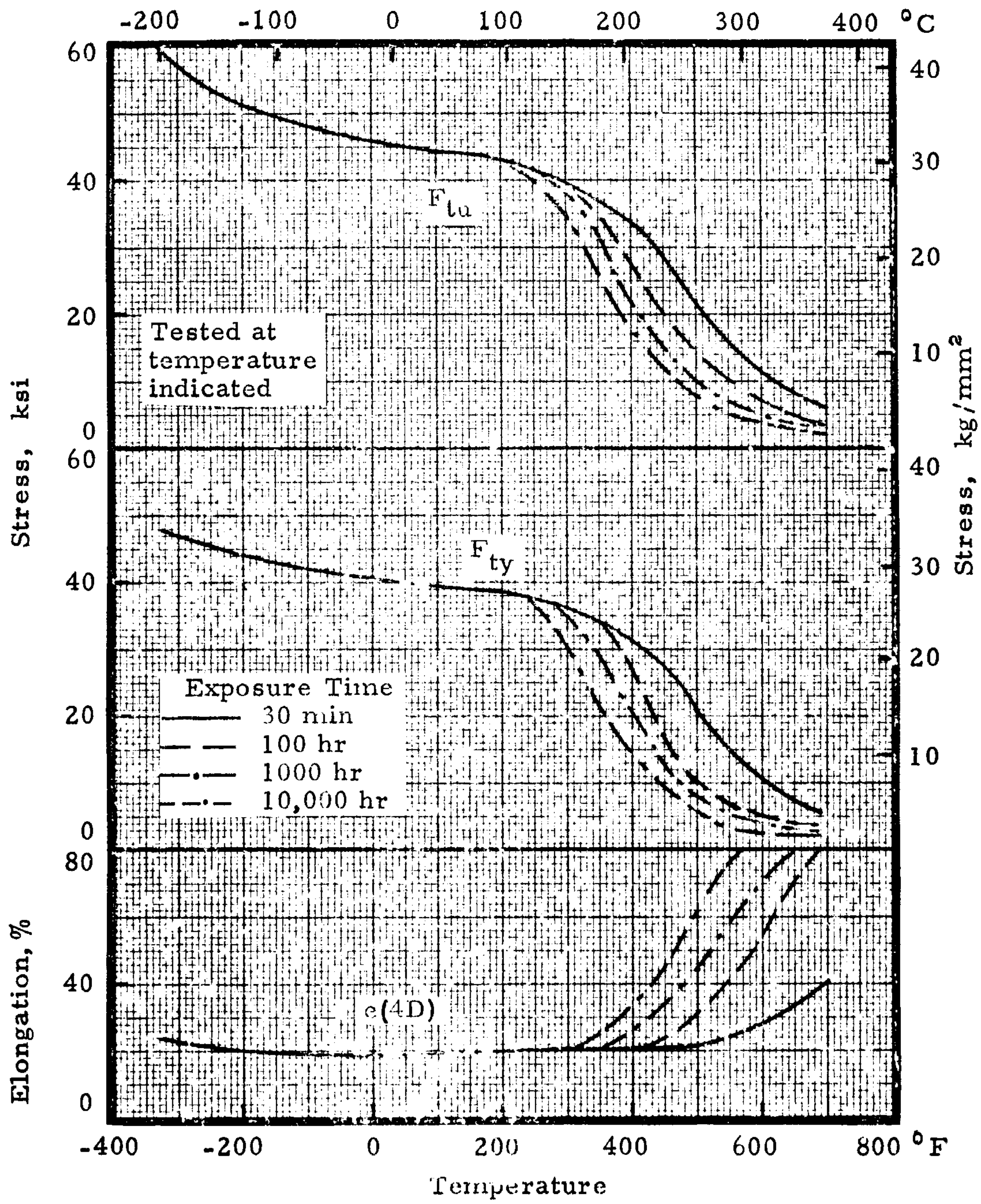

FIGURE 7.4133. — Effect of exposure and test temperature on tensile properties of 6061-T6.

(Ref. 7.10)

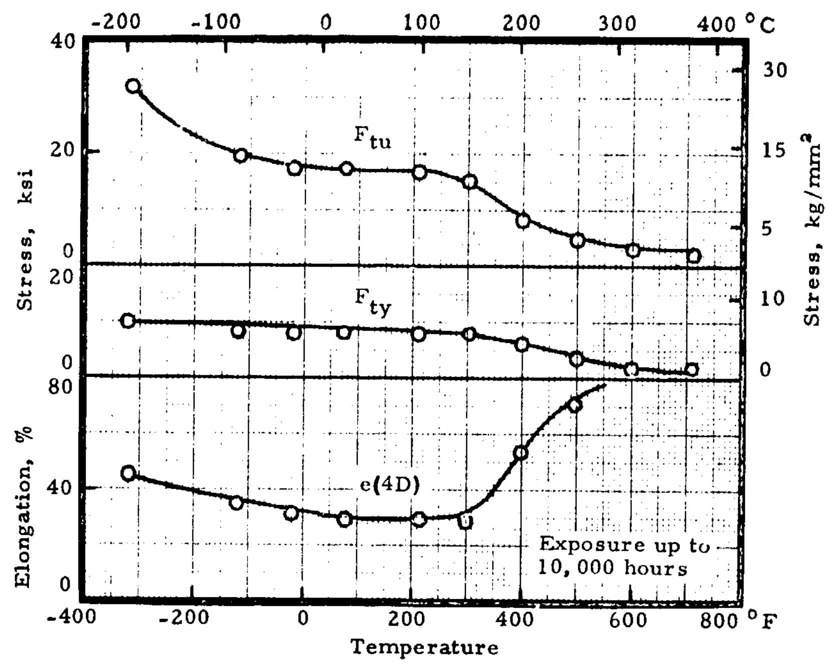

FIGURE 7.4134. – Effect of exposure and test temperature on tensile properties of 6061-O. (Ref. 7.11)

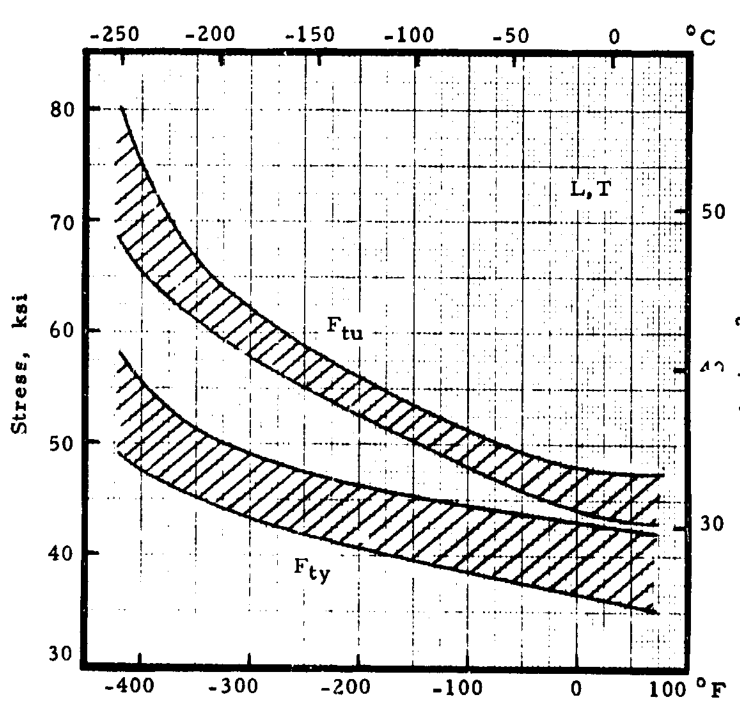

FIGURE 7.4135. – Effect of cryogenic temperatures on tensile properties of 6061-T6 sheet and forgings; sheet, 0.062-0.125 inch (1.57-3.18 mm). (Refs. 7.9, 7.12, 7.13, 7.14)

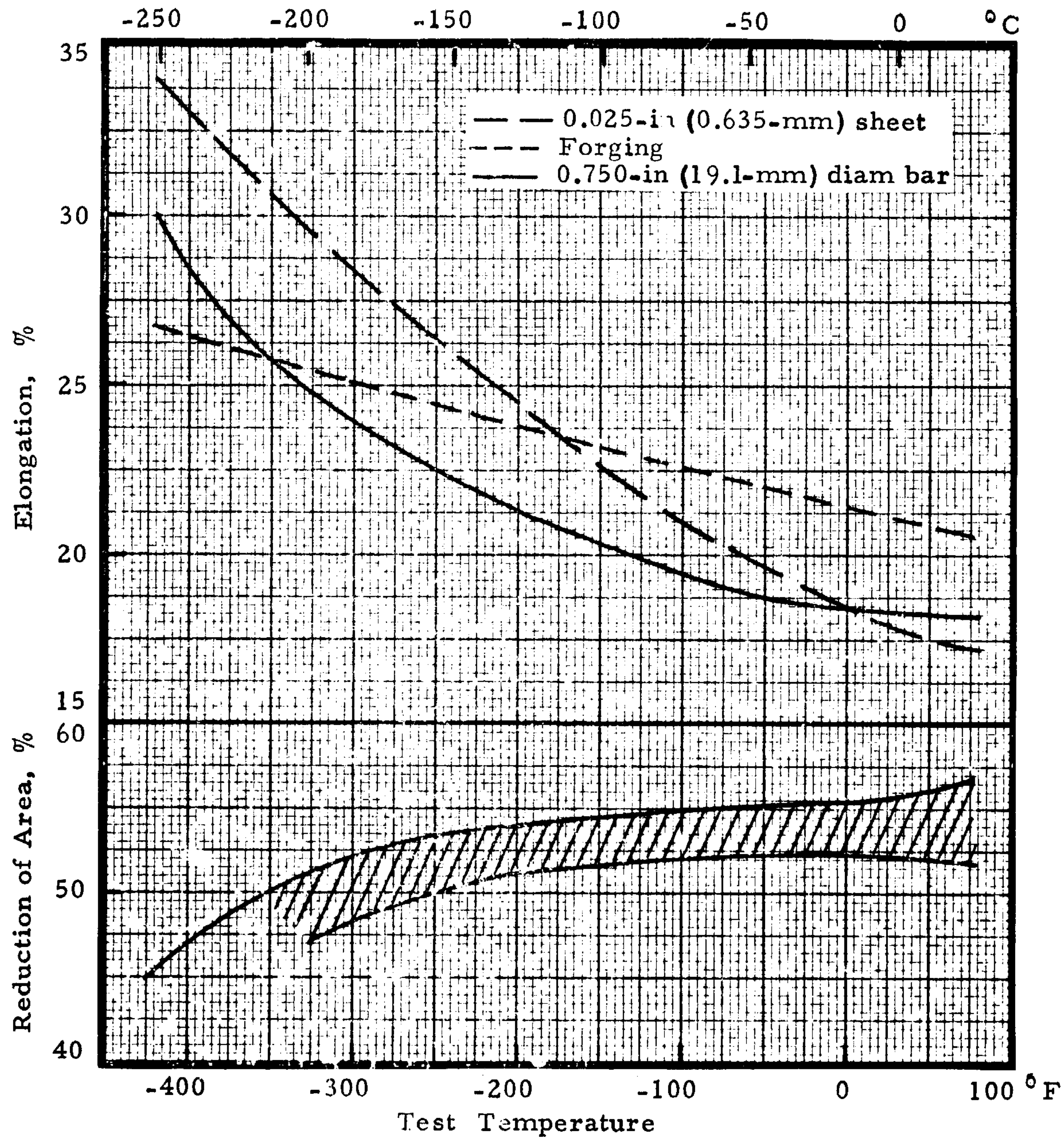

FIGURE 7.4136. — Effect of cryogenic temperatures on tensile elongation and reduction of area of 6061-T6.

(Refs. 7.14, 7.15, 7.16, 7.17)

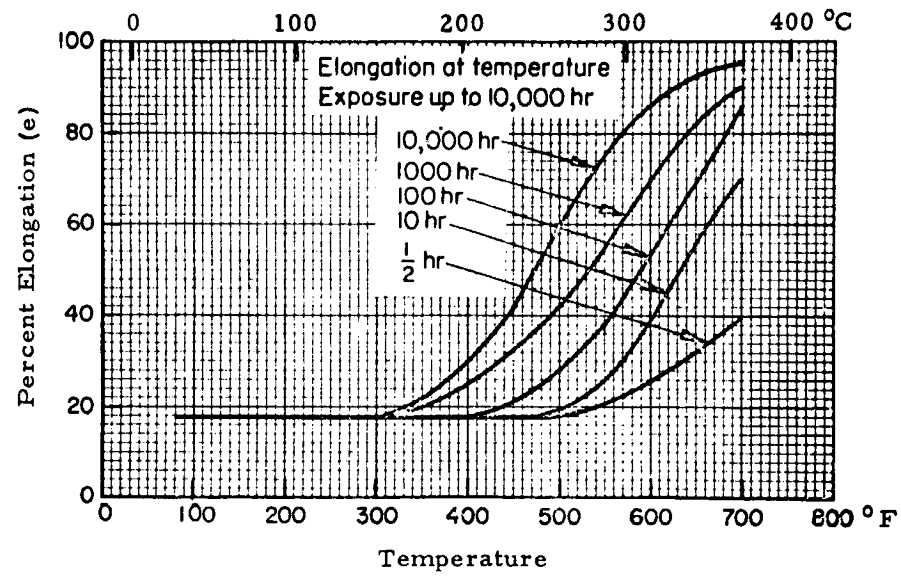

FIGURE 7.4137. – Effect of temperature on the elongation of 6061-T6 (all products). (Ref. 7.4)

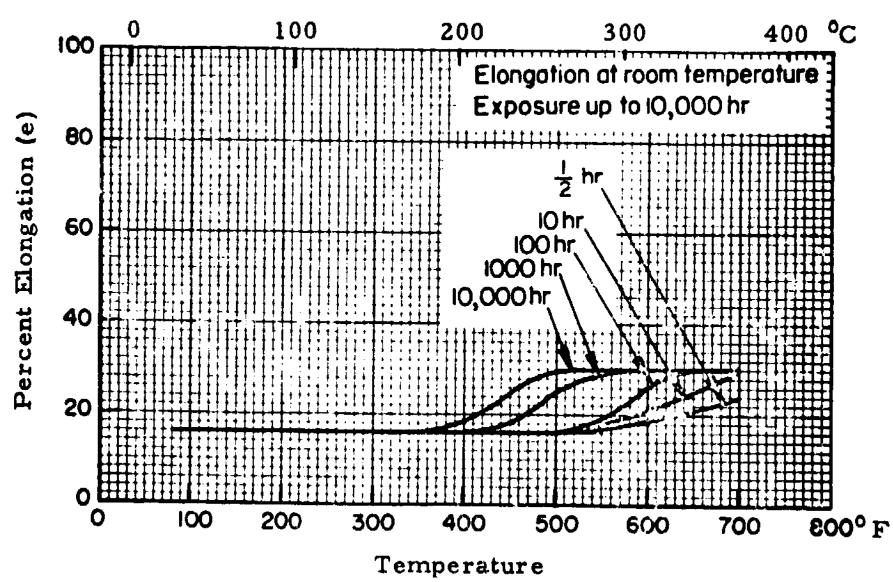

FIGURE 7.4138. – Effect of exposure at elevated temperatures on the elongation of 6061-T6 (all products). (Ref. 7.4)

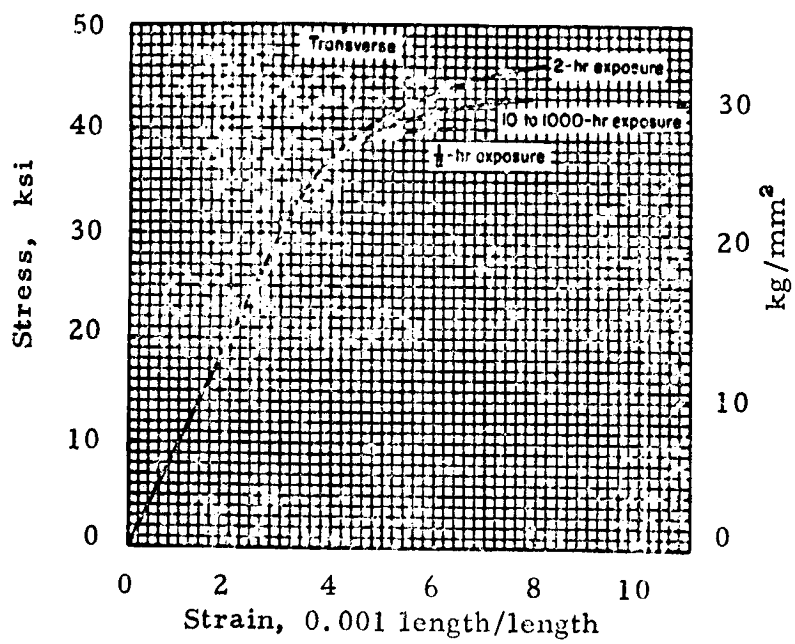

FIGURE 7.4221. – Typical compressive stress-strain curves for clad 6061-T6 sheet at 200° F (93° C).

(Ref. 7.4)

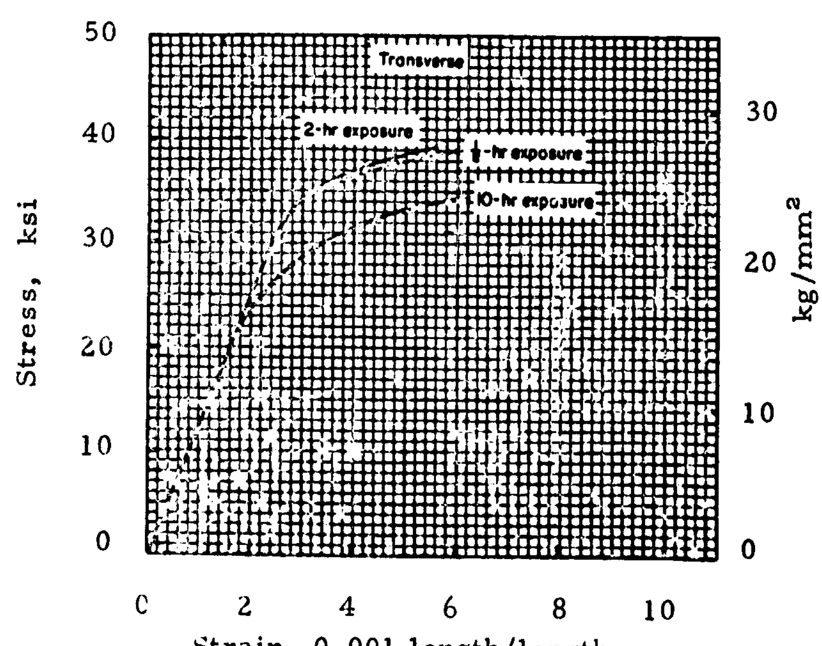

FIGURE 7.4222. – Typical compressive stress-strain curves for clad 6061-T6 at 300° F (149°C).

(Ref. 7.4)

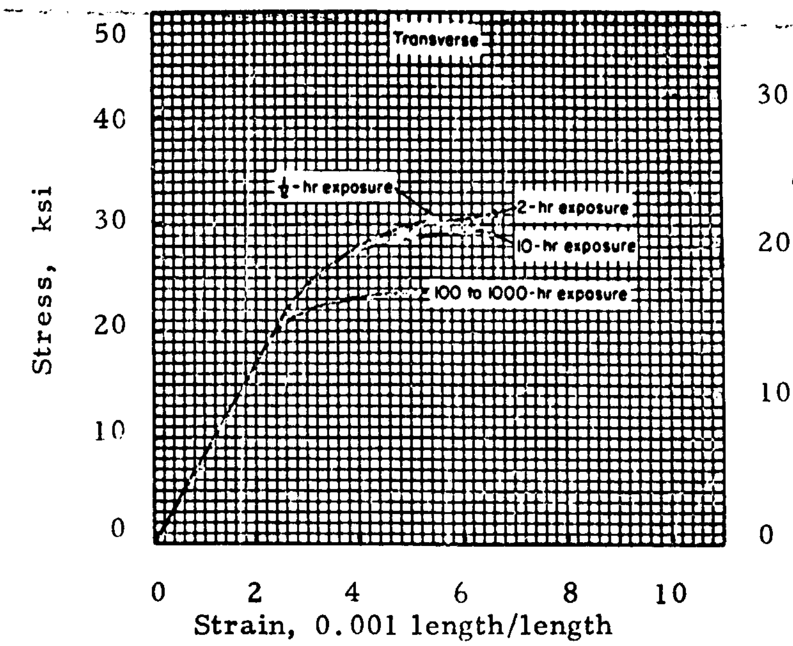

FIGURE 7.4223. – Typical compressive stress-strain curves for clad 6061-T6 sheet at 400°F (204°C).

(Ref. 7.4)

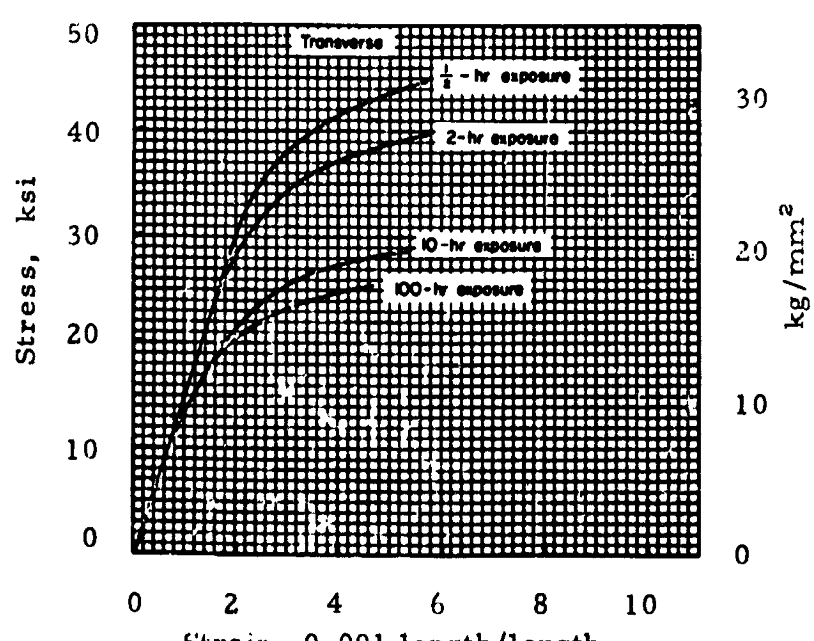

FIGURE 7.4224. – Typical compressive stress-strain curves for clad 6061-T6 sheet at 500°F (260°C).

(Ref. 7.4)

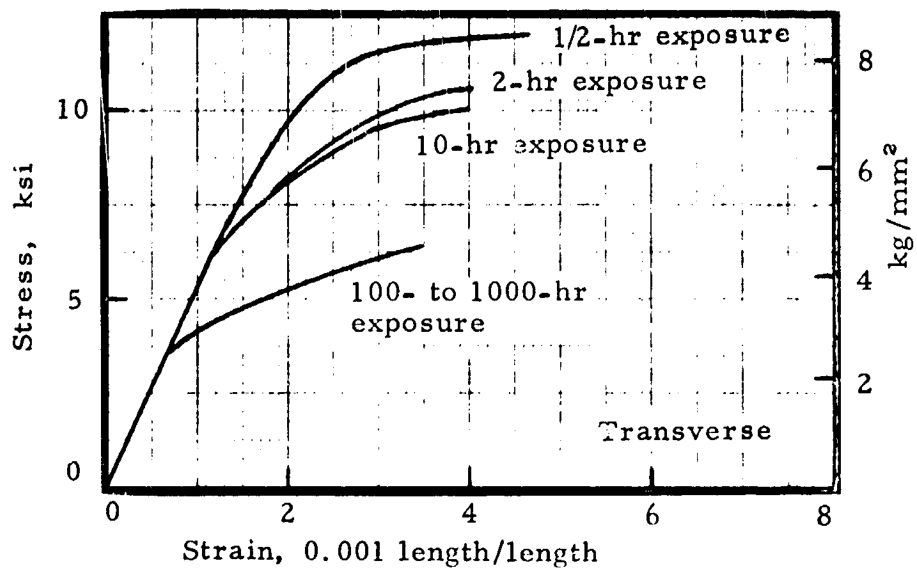

FIGURE 7.4225. – Typical compressive stress-strain curves for clad 6061-T6 sheet at 600° F (316° C).
(Ref. 7.4)

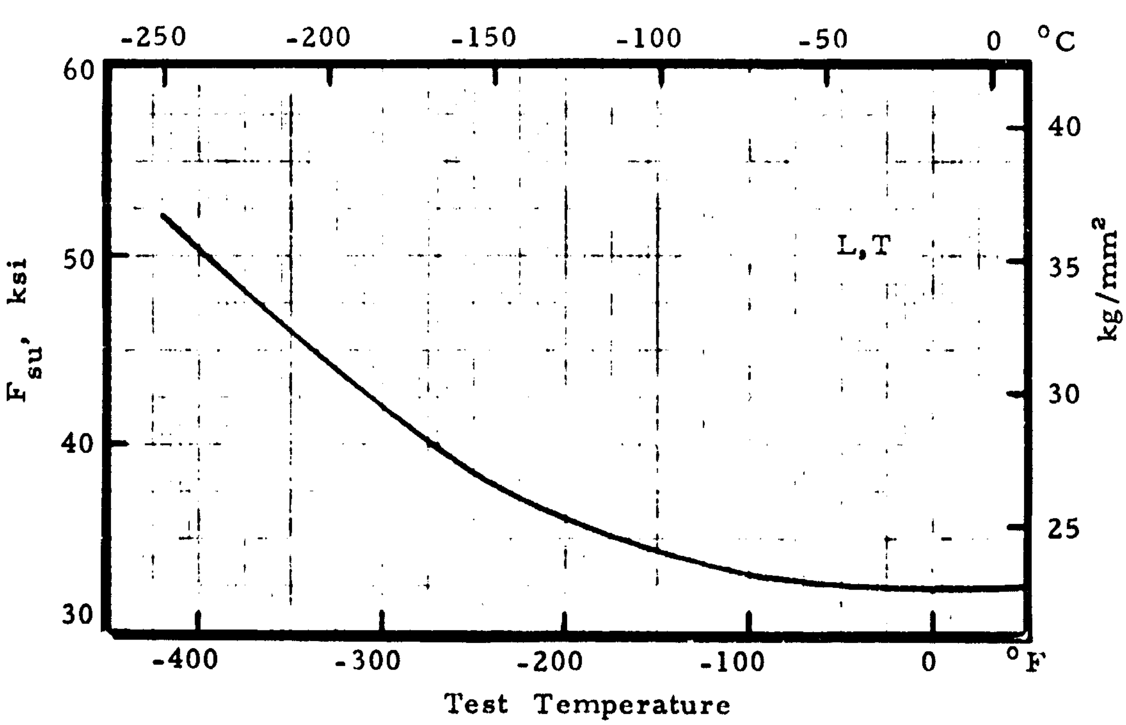

FIGURE 7.4412. – Effect of low temperature on shear strength of 6061-T6 sheet, 0.100-in (2.54-mm).
(Ref. 7.9)

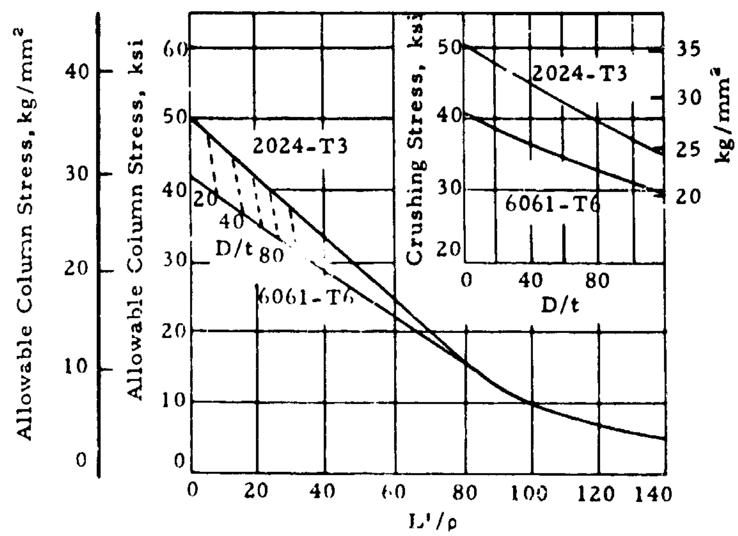

FIGURE 7.4512. – Allowable column stress (F_c) and crushing stress (F_{cc}) for round 6061-T6 (and 2024-T3) tubing.
(Ref. 7.4)

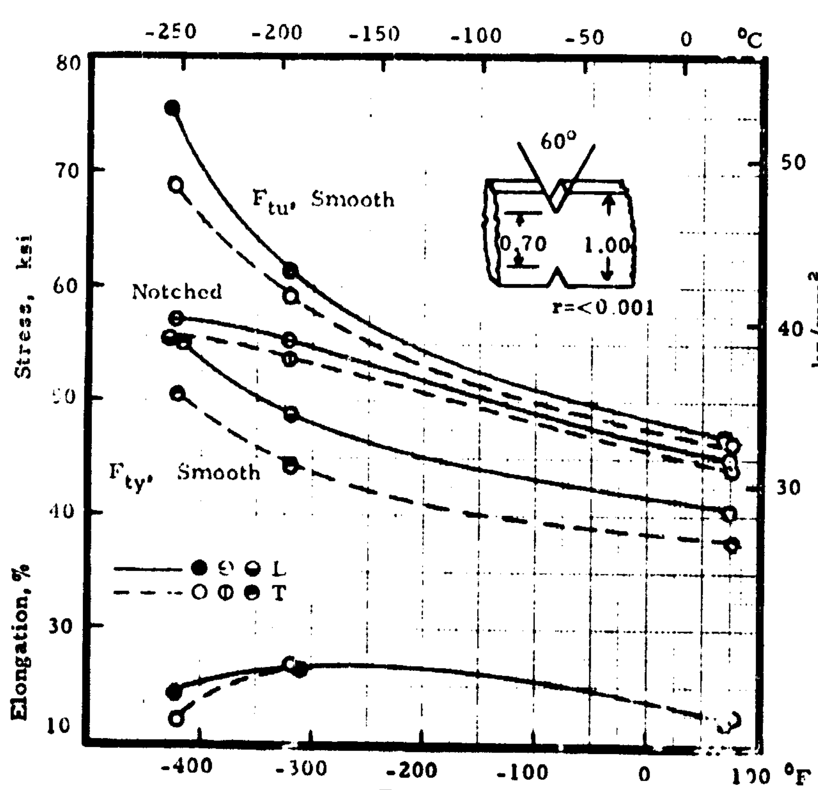

FIGURE 7.4611. – Effect of test temperature on smooth and notched tensile properties of 6061-T6 sheet; 0.125-in (3.175-mm).
c (Ref. 7.12)

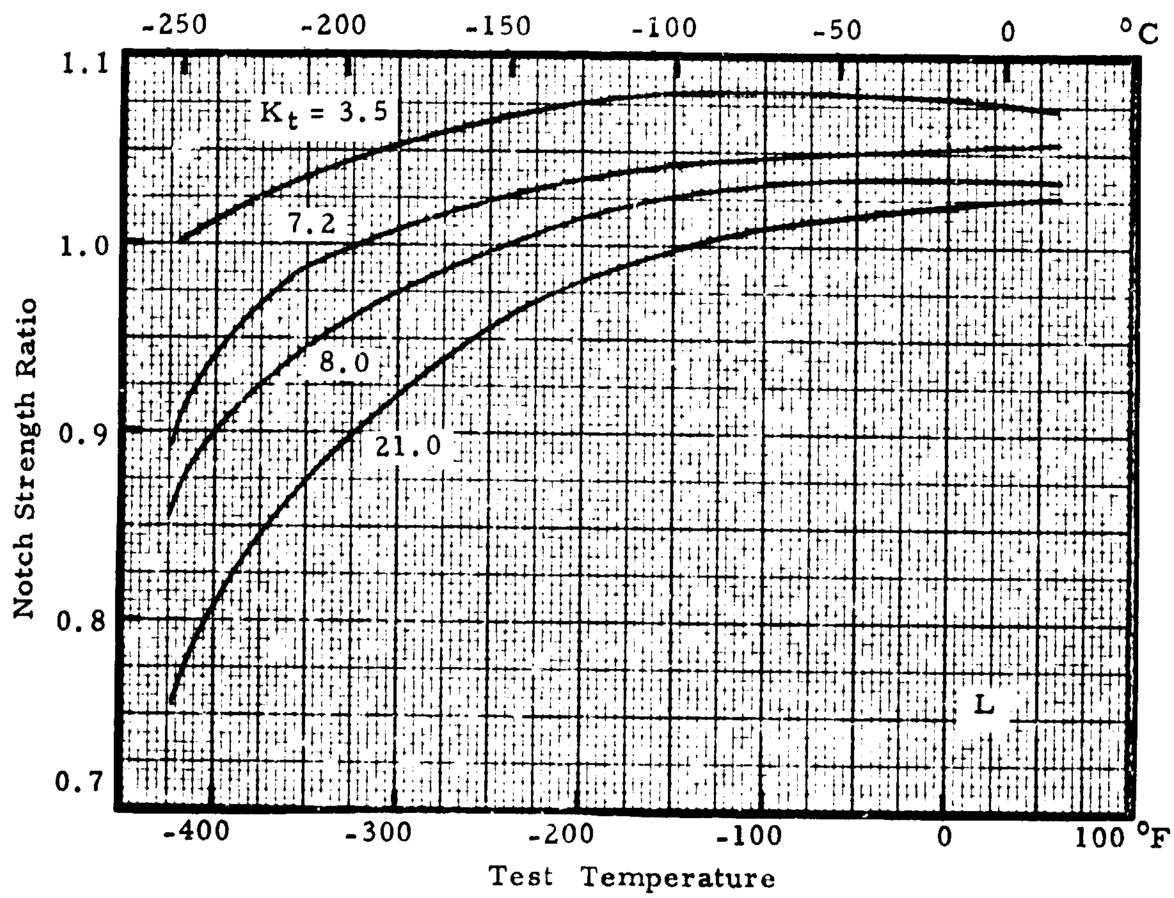

FIGURE 7.4612. – Effect of cryogenic temperatures on notch strength ratio of 6061-T6 sheet, 0.020-0.125 inch (0.508-3.175 mm).

(Refs. 7.9, 7.12, 7.18)

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Chapter 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General

8.2 Specified Properties

8.3 Impact

8.31 Effect of temperature on impact strength of T6 bar and plate, figure 8.31.

8.4 Creep

8.41 Creep and creep rupture properties of 6061 and 6062 in T6 condition, figure 8.41.

8.5 Stability (see also Chapter 7)

8.51 Effect of exposure to elevated temperature on room temperature tensile properties of 6061 and 6062 in T4 condition, figure 8.51.

8.52 Effect of exposure to elevated temperature on room temperature tensile properties of 6061 and 6062 in T6 condition, figure 8.52.

8.6 Fatigue

8.61 Rotating beam fatigue strength of alloy in T6 condition, figure 8.61.

8.62 Cantilever beam fatigue strength of alloy at elevated temperatures, figure 8.62.

8.63 Typical constant life fatigue diagram for various products, figure 8.63.

8.64 Fatigue strength of sharply notched and smooth machined round specimens under completely reversed flexure, figure 8.64.

8.65 S-N curves at room temperature for T6 sheet and round specimens, figure 8.65.

8.66 S-N curves for bar at room temperature and cryogenic temperatures, figure 8.66.

8.67 S-N curves for sheet at room and cryogenic temperatures, figure 8.67.

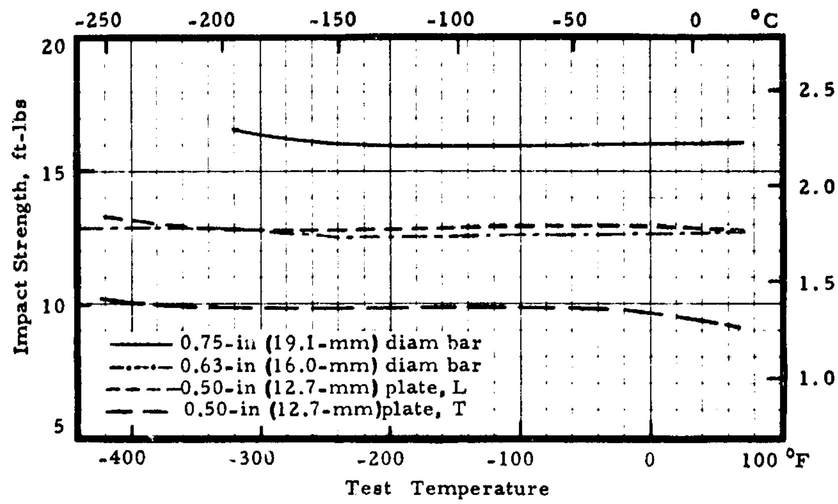

FIGURE 8.31. – Effect of cryogenic temperatures on Charpy V impact strength of 6061-T6 bar and plate.

(Refs. 8.2, 8.3, 8.11)

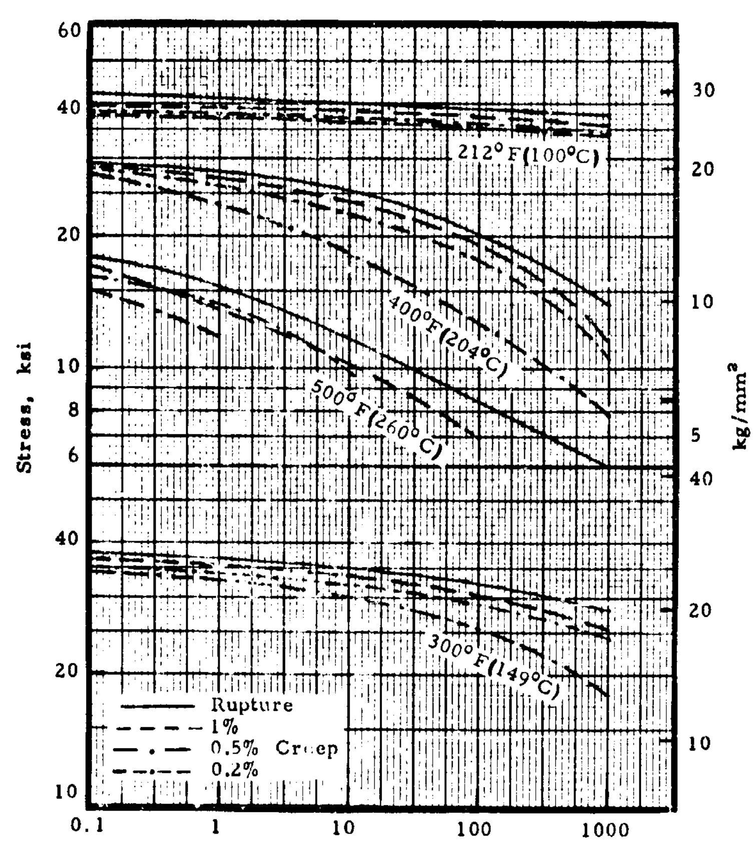

FIGURE 8.41. – Creep and creep rupture properties of 6061-T6 and 6062-T6 at elevated temperatures.

(Ref. 8.4)

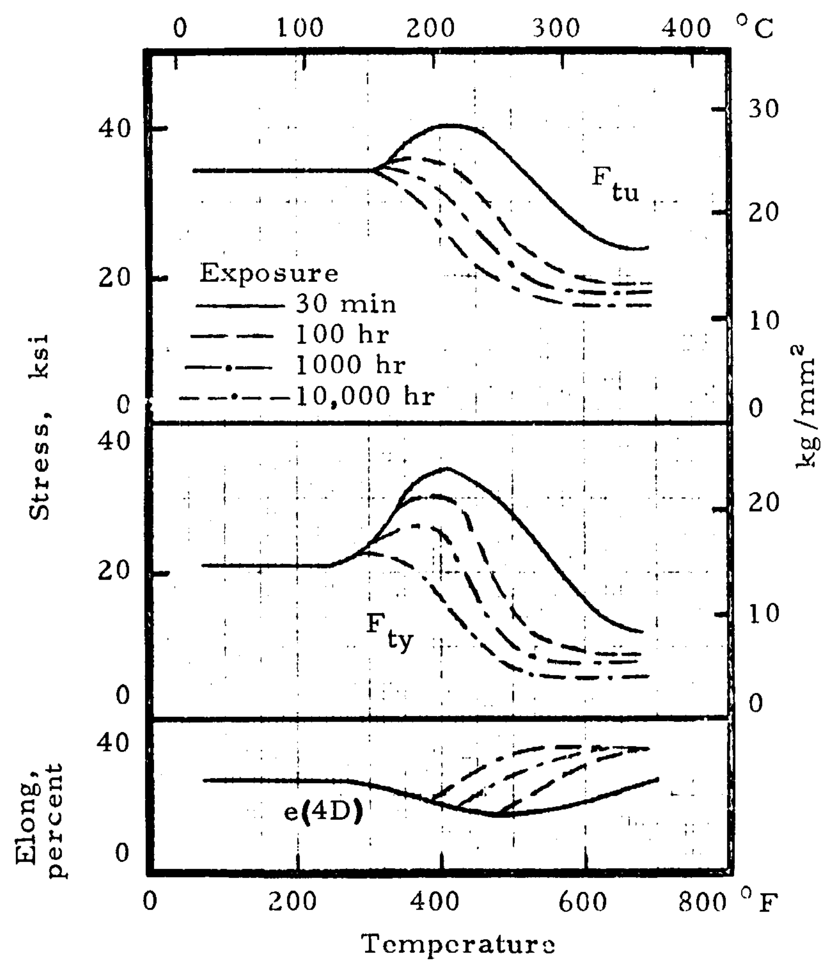

FIGURE 8.51. — Effect of exposure to elevated temperature on room temperature tensile properties of 6061-T4 and 6062-T4.

(Ref. 8.5)

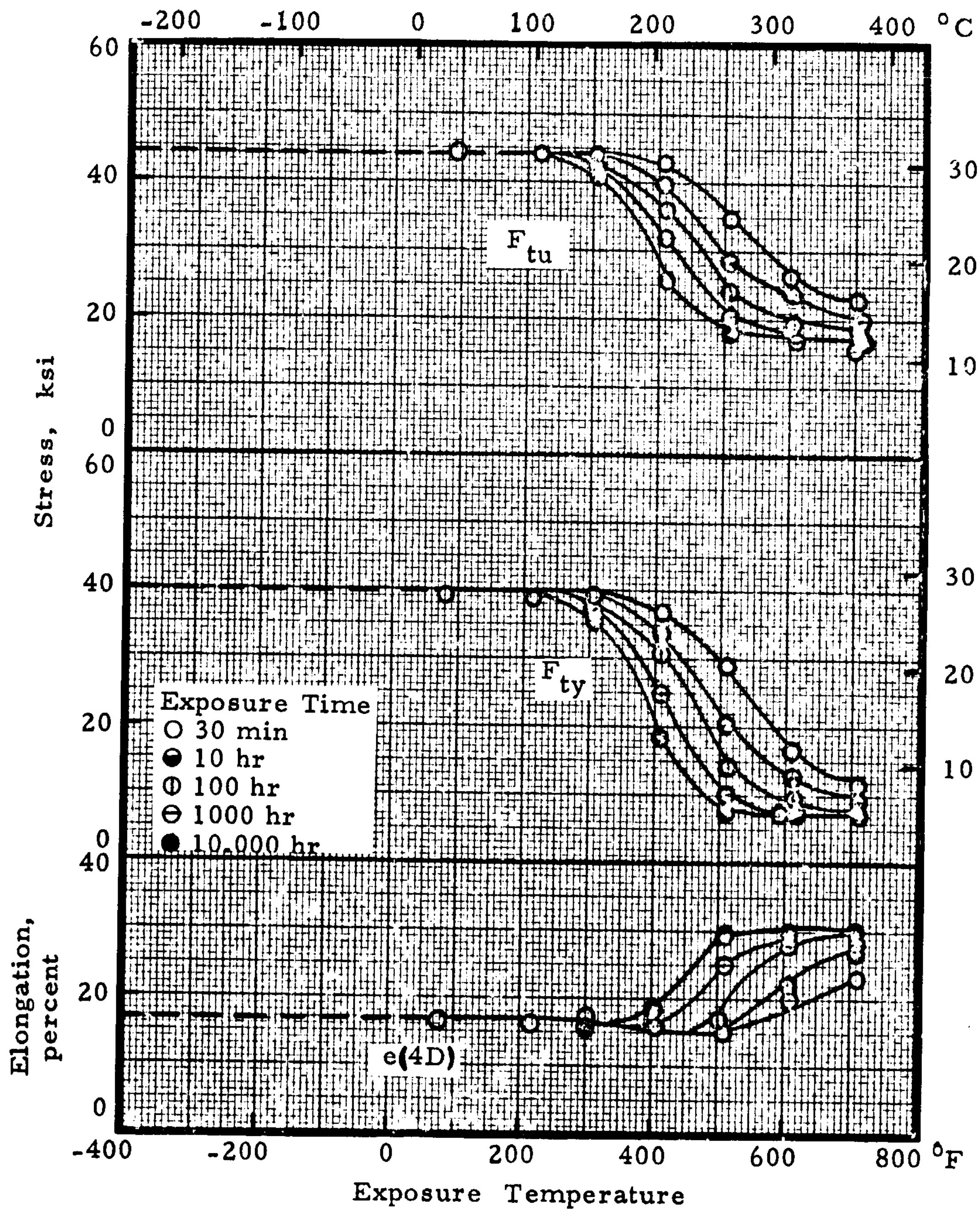

FIGURE 8.52. — Effect of exposure to elevated temperature on room temperature tensile properties of 6061-T6 (all products).

(Ref. 8.10)

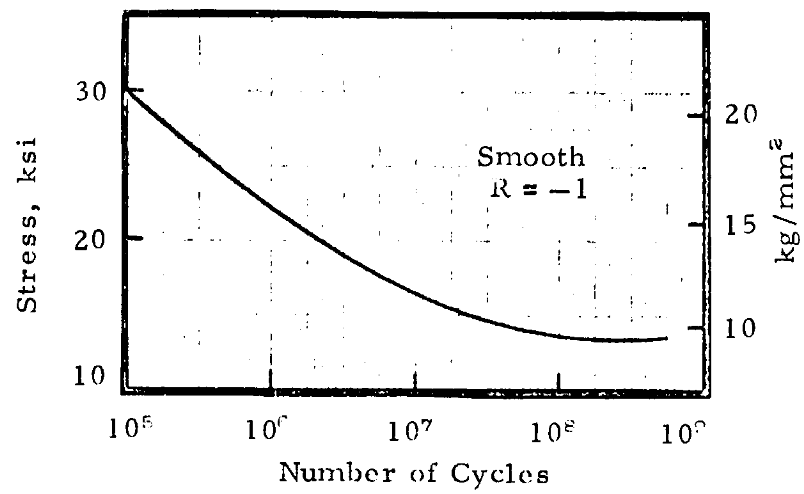

FIGURE 8.61. — Rotating beam fatigue strength of 6061-T6 and 6062-T6.

(Ref. 8.4)

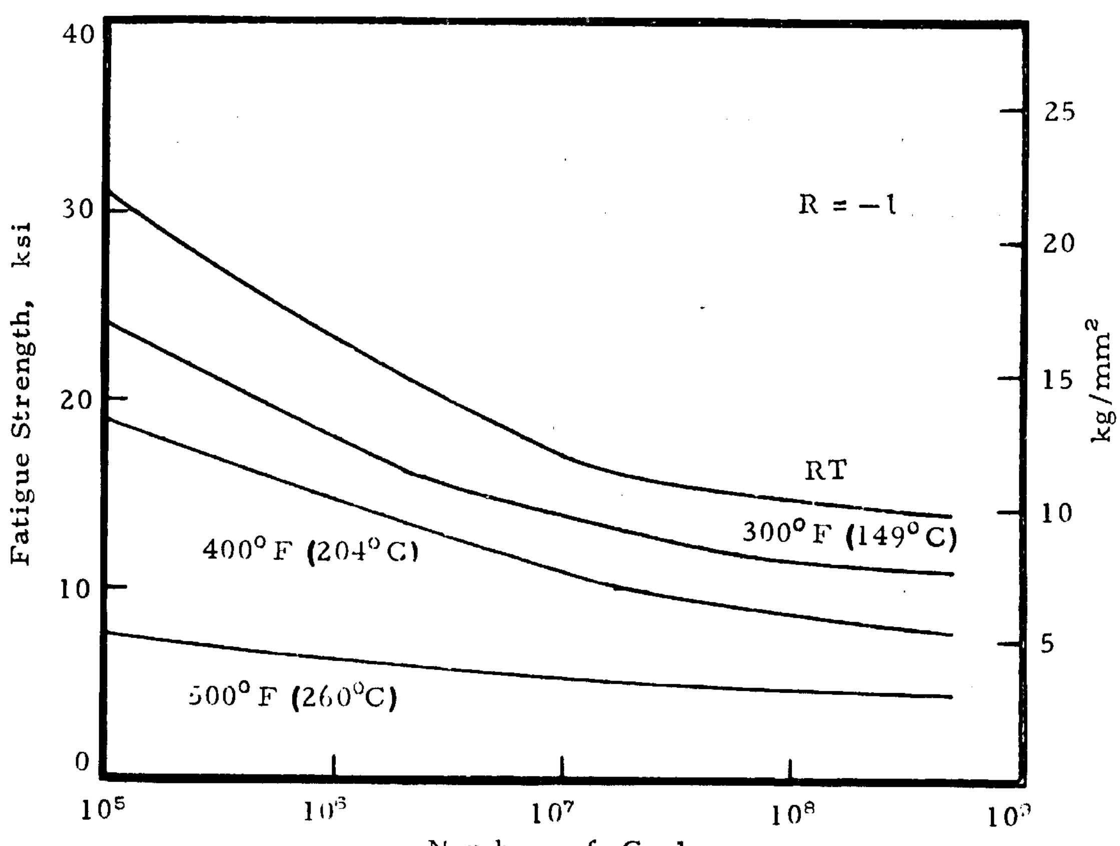

FIGURE 8.62. — Cantilever beam fatigue strength of 6061-T6 at elevated temperatures.

(Ref. 8.6)

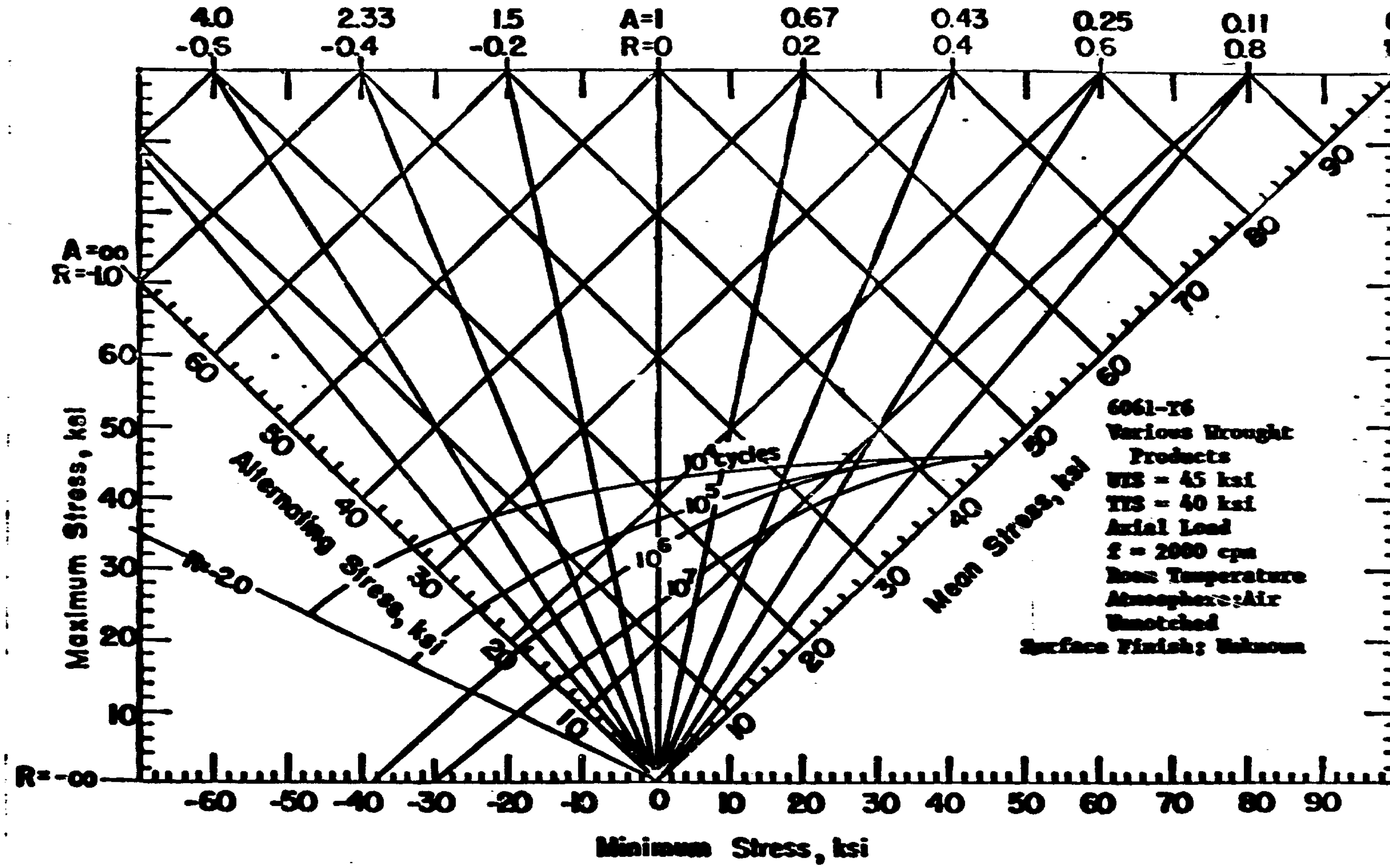

FIGURE 8.63. — Typical constant-life diagram for fatigue behavior of various wrought 6061-T6 products.

Note: 1 ksi = 0.70307 kg/mm² (Ref. 8.6)

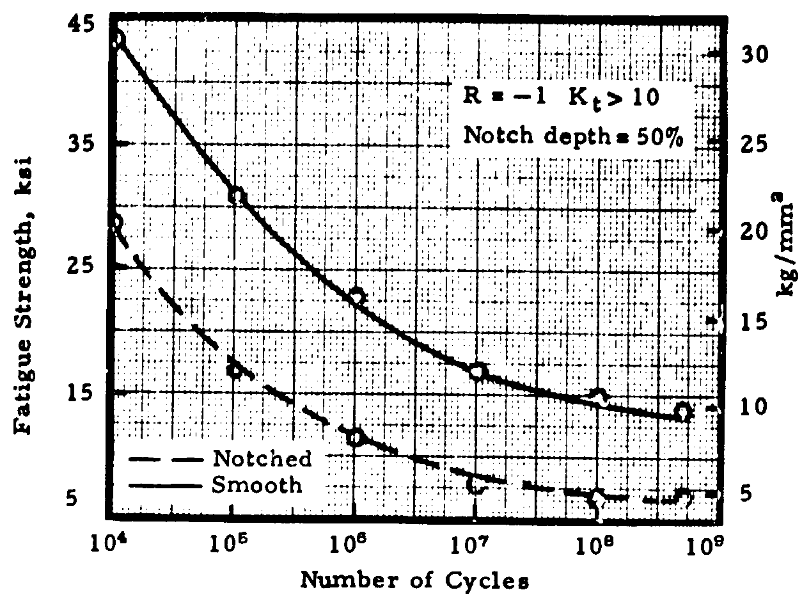

FIGURE 8.64. — Fatigue strength of sharply notched and smooth machined round 6061-T6 specimens under completely reversed flexure (R. R. Moore tests).

(Ref. 8.6)

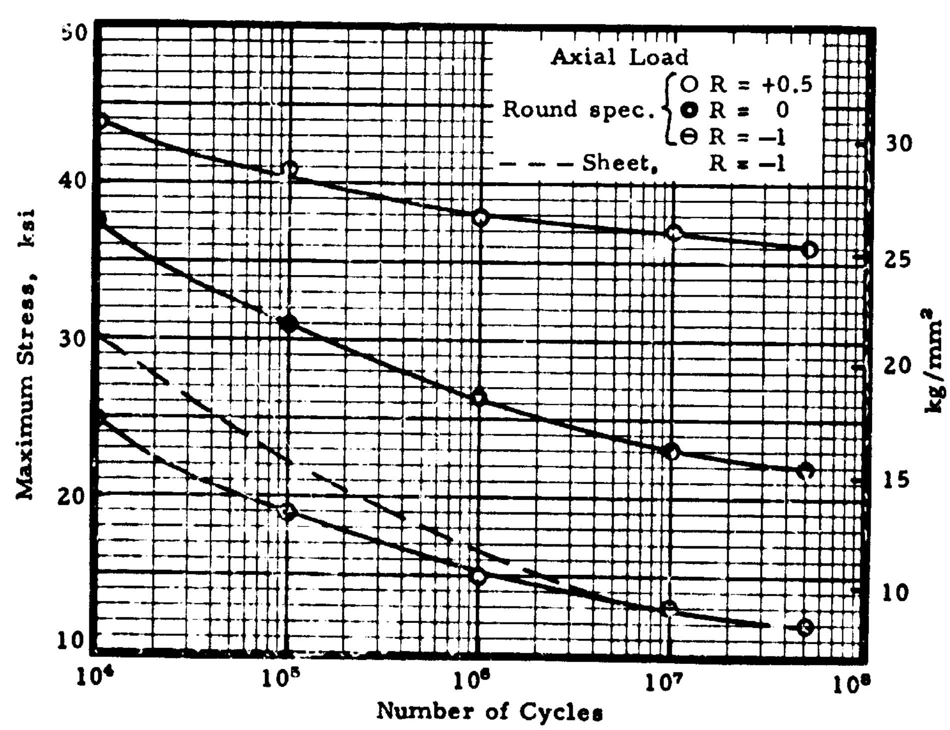

FIGURE 8.65. — S-N curves at room temperature for 6061-T6 sheet and round specimens; sheet, 0.064 in (1.63 mm).

(Ref. 8.6)

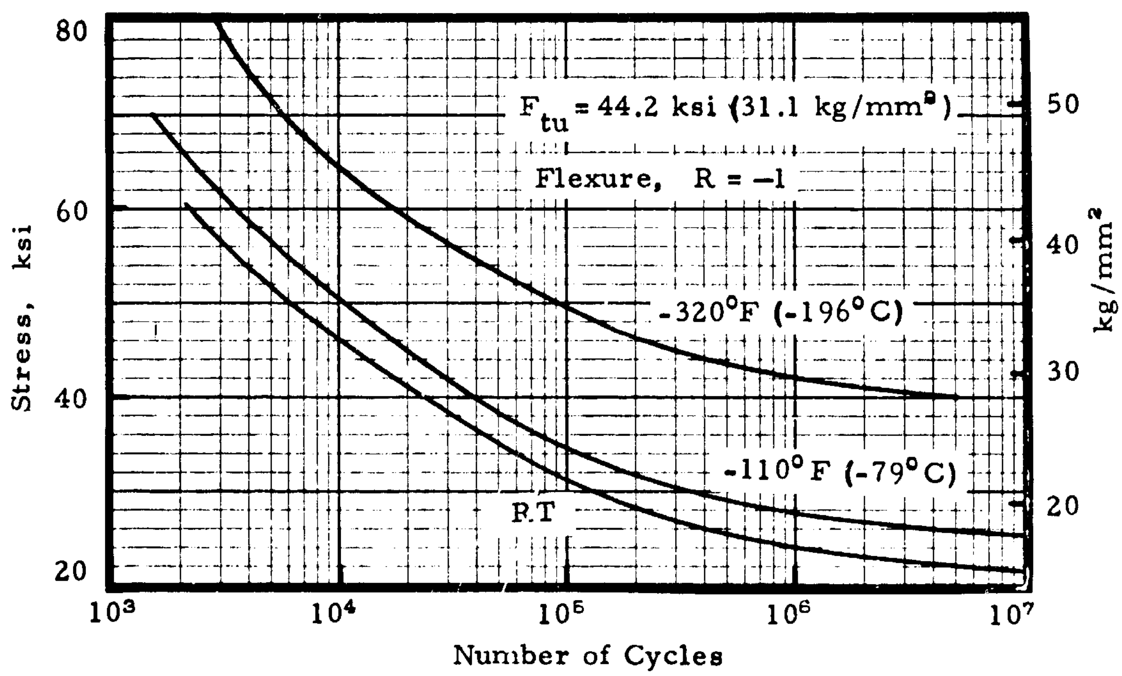

FIGURE 8.66. — S-N curves for 0.75-in (19.1-mm) diam 6061-T6 bar at room and cryogenic temperatures.

(Refs. 8.7, 8.8, 8.9)

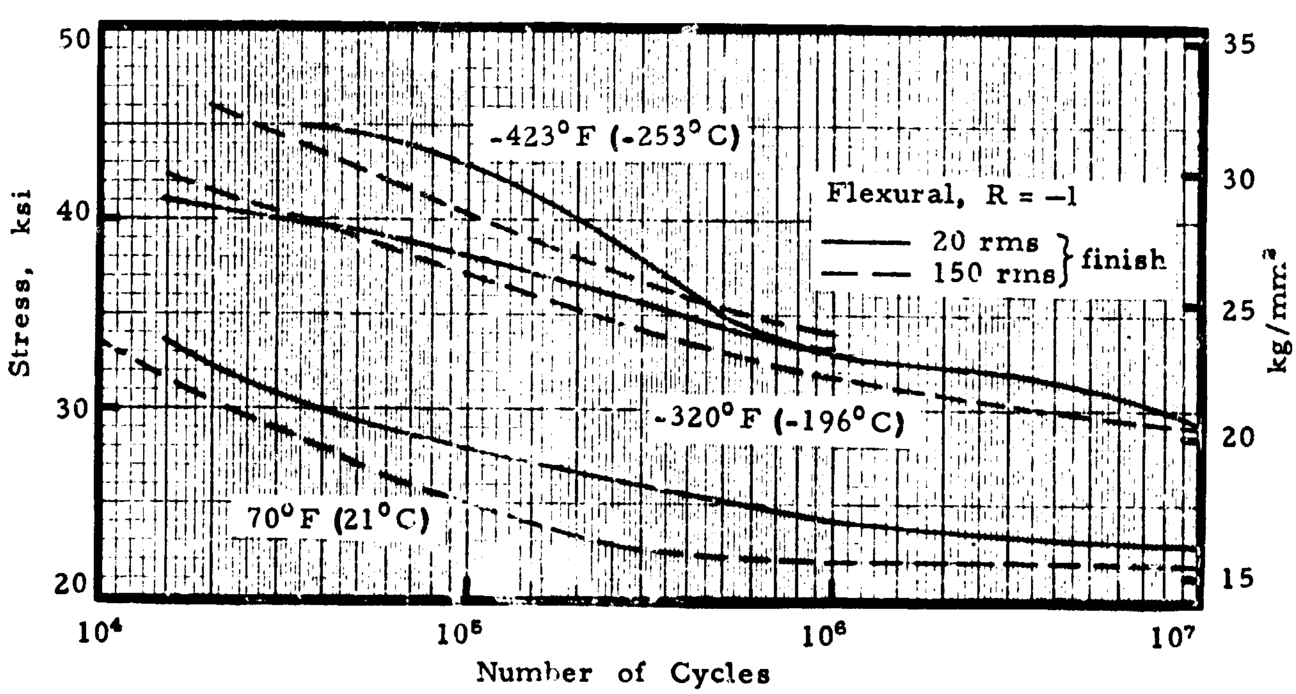

FIGURE 8.67. — S-N curves for 6061-T6 sheet (0.050-in, 1.27-mm) at room and cryogenic temperatures.

(Ref. 8.12)

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Chapter 9

PHYSICAL PROPERTIES

9.1 Density (ρ)

$0.098\ lb/in^3$ at 68°F; $2.70\ g/cm^3$ at 20°C (ref. 9.1, 9.2).

9.2 Thermal Properties

9.21 Thermal conductivity, K,

O temper	0.43 cal/cm/sec/cm²/°C
	1250 Btu/in/ft²/°F/hr
T4 temper	0.37 cal/cm/sec/cm²/°C
	1070 Btu/in/ft²/°F/hr
T6 temper	0.40 cal/cm/sec/cm²/°C
	1160 Btu/in/ft²/°F/hr

9.22 Average coefficient of thermal expansion, α, figure 9.22

68°F to 212°F	13.0×10^{-6} in/in/°F
20°C to 100°C	23.4×10^{-6} cm/cm/°C (ref. 9.1)

9.221 Thermal expansion at low temperatures, figure 9.221.

9.23 Specific heat, c_p

0.23 cal/g °C at 100°C; 0.23 Btu/lb °F at 212°F (refs. 9.1, 9.2)

9.24 Thermal diffusivity. Data may be calculated according to the equation: Diffusivity = $K/\rho c_p$

9.3 Electrical Properties

9.31 Electrical resistivity at 20°C

O temper	3.7 microhm-cm
T4 temper	4.3 microhm-cm
T6 temper	4.0 microhm-cm (ref. 9.10)

9.4 Magnetic Properties

9.41 Permeability. The alloy is nonmagnetic.

9.5 Nuclear Properties. Nuclear data were found only for 6063. Because of the similarity in chemistry of 6061 and 6063 (both are aluminum-magnesium-silicide alloys), data on 6063 are presented below:

9.51 Microscopic thermal-neutron cross section, 0.23 barns/atom, Macroscopic thermal-neutron cross-section, $0.012\ cm^{-1}$ (ref. 9.5).

9.52 Effect of irradiation on tensile properties, table 9.52.

9.6 Other Physical Properties

9.61 Emissivity, in air at 77°F (25°C), 0.035 to 0.07 (ref. 9.7)

9.62 Damping capacity (no data found).

TABLE 9.52. — Effect of Irradiation on Tensile Properties

Source	Refs. 9.6, 9.11													
Alloy	6061													
Temper	Fast Fluence, n/cm^2	Temp. (a)		F_{ty}, ksi (b)		F_{tu}, ksi (b)		NTS, ksi (b)		Total elongation, %		Redn. in Area, %		
		°F	°C	Unirr.	Irrad.	Unirr.	Irrad.	Unirr.	Irrad.	Unirr.	Irrad.	Unirr.	Irrad.	
O	10^{18}	149	65	9.5	25.6	18.1	37.3	-	-	28.8	22.4	-	-	
T6	10^{18}	120	49	40.0	42.8	47.2	51.9	-	-	21.0	22.0	-	-	
T6, L	5.0×10^{16}	-257	-161	46.5	55.0	64.7	69.0	61.4	65.8	24.1	27.5	34.4	32.6	
TW	5.0×10^{16}	-257	-161	47.4	57.6	67.3	71.6	56.5	65.2	9.0	11.2	16.4	21.5	
LW	5.0×10^{16}	-257	-161	56.9	52.6	68.9	66.7	57.2	67.6	6.0	10.2	11.9	10.8	
	1.0×10^{17}	-257	-161	50.4	59.4	68.1	64.6	73.0	-	30.0	30.0	41.4	34.0	

(a) Exposure temperature same as test temperature

(b) 1 ksi = 0.70307 kg/mm^2

L = longitudinal
T = transverse
W = welded

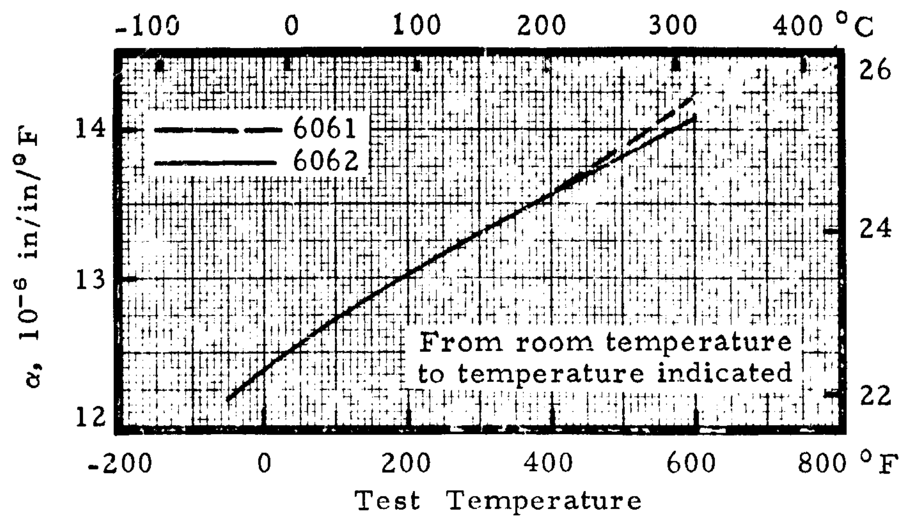

FIGURE 9.22. — Mean coefficient of thermal expansion of 6061 and 6062. (Refs. 9.3, 9.4)

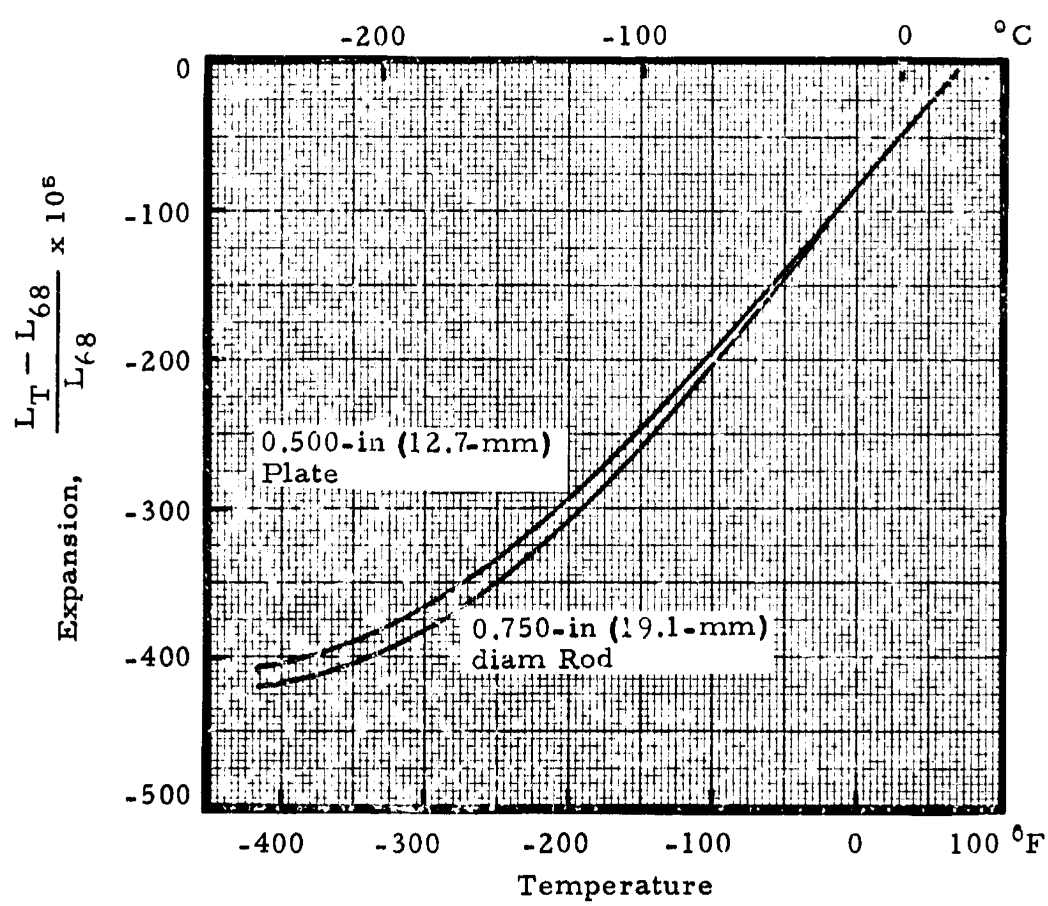

FIGURE 9.221. — Thermal expansion of 6061-T6 rod and plate at low temperatures. (Refs. 9.8, 9.9)

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Chapter 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. Despite its high chemical reactivity and affinity for oxygen, aluminum exhibits excellent resistance to corrosion in most common environments because it passivates spontaneously under normal oxidizing conditions. The passive film is a hard, strongly adhering layer of aluminum oxide, estimated as $20\text{-}100 \times 10^{-7}$ mm thick on aluminum exposed to air (ref. 10.1), which protects the metal from direct attack. Thus, the corrosion rate of aluminum generally decreases with time, except under severe or specific exposure conditions which tend to disrupt the passive film. Outdoors, aluminum and its alloys weather to a pleasant gray color, with some initial superficial pitting which gradually ceases (ref. 10.2). Industrial soot, sulfur dioxide, sulfur trioxide, and marine spray tend to increase atmospheric corrosion, but hydrogen sulfide and carbon dioxide do not (ref. 10.3). Twenty-year tests at several marine and industrial and rural sites have shown that atmospheric attack on aluminum takes place principally in the first year and progresses very slowly beyond the second year (ref. 10.4). Even at high temperatures in dry atmospheres, aluminum is highly resistant to most common gases, except the halogens (ref. 10.2). However, in studies of the effects of various atmospheric constituents, it has been shown that water vapor is a principal corrosive agent, causing loss of fatigue properties and acceleration of crack propagation rates during fatigue tests (ref. 10.12).

In aqueous environments, corrosion resistance of aluminum is greatest under neutral or slightly acid conditions, where the protective oxide film is most stable (pH 5.5-8.5 at room temperature, 4.5-7 at 95°C) (refs. 10.1, 10.5). Strong alkalies and strong-non-oxidizing acids destroy the oxide and greatly accelerate corrosion. Pitting attack occurs in waters containing chloride or other halogen ions, particularly at crevices or stagnant areas where passivity breakdown is accelerated by differential aerative effects. Traces of copper, iron, and mercury ions are also effective in promoting localized attack via galvanic cells formed between aluminum and metal deposited by replacement reactions (ref. 10.1). Since aluminum is strongly anodic to most other common metals, galvanic coupling with them generally produces severe attack on the aluminum, especially in sea water (ref. 10.2).

Aluminum and its alloys are rather resistant to most molten salts. However, molten metals generally attack aluminum, particularly zinc and tin, which form alloys (ref. 10.2). Even a small amount of mercury is especially harmful, since it breaks down passivity and amalgamates, causing rapid perforation of aluminum piping or sheet (ref. 10.1). Under some conditions, aluminum exhibits very poor resistance to chlorinated solvents and may even react explosively with them; however, such solvents, when properly inhibited, may be used for cleaning and degreasing without harm (ref. 10.6).

Aluminum purity significantly affects its corrosion resistance. High purity metal is more resistant than commercially pure aluminum, which in turn is generally more resistant than most alloys (ref. 10.1). Corrosion resistance of specific alloys is affected by composition, heat treatment and stress conditions, as discussed further below.

10.2 Aluminum-Magnesium-Silicon Alloys. The aluminum-magnesium-silicon alloys, such as 6061, contain magnesium and silicon in a ratio which forms a magnesium silicide compound. These alloys also contain small amounts of such elements as copper, manganese, chromium, zinc, and titanium. The compositions were formulated to enhance certain characteristics such as strength, formability, etc., without affecting resistance to corrosion. Magnesium and silicon in solid solution, in the ratio of the compound Mg_2Si do not affect the electrode potential of the alloy as shown in table 10.1 for 6061 alloy. Thus, these alloys have good resistance to corrosion, similar to commercially pure aluminum (ref. 10.7).

10.3 Behavior of 6061 Alloy. The 6061 alloy exhibits the best resistance to corrosion of the heat-treatable aluminum alloys. It has a high resistance to rural atmospheres and good resistance to weathering in industrial and marine atmospheres. Also, corrosion resistance of this alloy is independent of temper. The degree and nature of attack in other environments is influenced by factors such as severity of environment, temperature, etc. Extensive information does not appear to be available on the resistance of 6061 to various chemicals and compounds. The alloy has been used successfully for many years, however, in the construction of equipment for processing or handling industrial chemicals as listed in table 10.2. The alloy is attacked by severe environments such as aqua regia, hydrochloric acid, hydrofluoric acid, lithium hydroxide, perchloric acid, potassium cyanide, potassium and sodium hydroxide, and various mercury compounds.

10.31 As indicated above, water vapor appears to affect the rate of crack propagation (especially at low stress intensities) but does not affect the crack initiation period (ref. 10.12). To confirm this conclusion, fatigue tests were performed on 6061-T6 in two environments, dry and moist. Part of the test was run in one environment and the balance in the other. The resultsof these tests are shown in figure 10.31. The nature of the atmosphere during the crack initiation stage had no effect on the total fatigue life. At 38 ksi (27 kg/mm^2), testing in moist air and then in dry air did not reduce the fatigue life until the number of cycles in moist air exceeded 28×10^3 (N_R). Similarly, testing in dry air and then moist air did not increase life until the number of cycles in dry air exceeded 28×10^3 (ref. 10.10).

10.32 A study was made of high velocity projectile penetrations of simulated propellant tanks made from 6061-T3 sheet to determine the impact sensitivity of this alloy in contact with liquid and solid rocket propellants. Thickness of tank walls was varied from 0.020 to 0.125 inch (0.508-3.175 mm). Projectiles used were primarily 0.219 inch (5.56 mm) diameter spheres of steel, and impacts were made at velocities of 5800 feet per second (1768 m/sec). It was found that no interaction occurred between the 6061-T3 tank wall and liquid oxygen. Also, no chemical reaction occurred between the 6061-T3 and hydrazine (N_2H_4) or the solid propellants Arcite 373 and Hercules CLW; high velocity impacts, however, did cause ignition of the Hercules CLW propellant (ref. 10.11).

The analysis of specimens of 6061-T6 stored at 110° F (44° C) with hydrazine and hydrazine-hydrazine nitrate mixture in sealed capsules for 4 years indicated excellent resistance to corrosion in these fuels (ref. 10.13). In some instances, incompatibility ratings were assigned because of excessive decomposition of the fuels, and it is cautioned that metal surfaces to be in contact with hydrazine fuels must be free of organic contamination or traces of catalytic metals or ions. In similar storage tests conducted with nitrogen tetroxide (ref. 10.14), 6061-T6 showed excellent resistance to corrosion and compatibility with the oxidizer.

10.4 Protective Measures

10.41 Under normal conditions and ordinary environments, 6061 alloy needs no surface protection. For more severe environmental conditions, clad material may be used for many applications. A common cladding material used is the 7072 alloy. Clad alloys have the corrosion resistance of the cladding material employed. Surface protection is discussed in greater detail in Chapter 11.

TABLE 10.1. — Electrode Potentials vs 0.1 N Calomel at 25°C

Source	Ref. 10.7
(Aqueous solution of 53 g NaCl and 3 g H_2O_2 per liter)	
Al + Mg + Si (1% Mg_2Si solid solution)	-0.83 volt
6061-T4	-0.80 volt
6061-T6	-0.83 volt
Clad 6061	-0.96 volt
Aluminum (99.5%)	-0.85 volt

TABLE 10.2. — Use of 6061-T6 in Chemical Industries

Source	Ref. 10.9
Process or Chemical	Equipment
Acetic acid	Storage tank cars, condensers, piping
Acetic anhydride	Tank cars, heat exchangers, reaction vessels
Ammonium nitrate	Ammonia tanks, evaporators, tank cars
Ammonium hydroxide	Absorbers, condensers, piping
Edible oils and fats	Deodorizers, bleachers, filters
Fatty acids	Trays, filter presses, melting vessels
Formaldehyde	Scrubbers, tanks, drums
Glue and gelatin	Vats, evaporators, tanks, screens
Naval stores	Stills, condensers, receivers, tanks
Refrigerants	Compressors, heat exchangers, tubing
Ammonia, carbon dioxide, Freons, soda ash manufacture	Heat exchangers, piping, absorbers
Water (distilled)	Storage tanks, receivers, degasifiers
Glycerin	Tank cars
Nitric acid	Tank cars

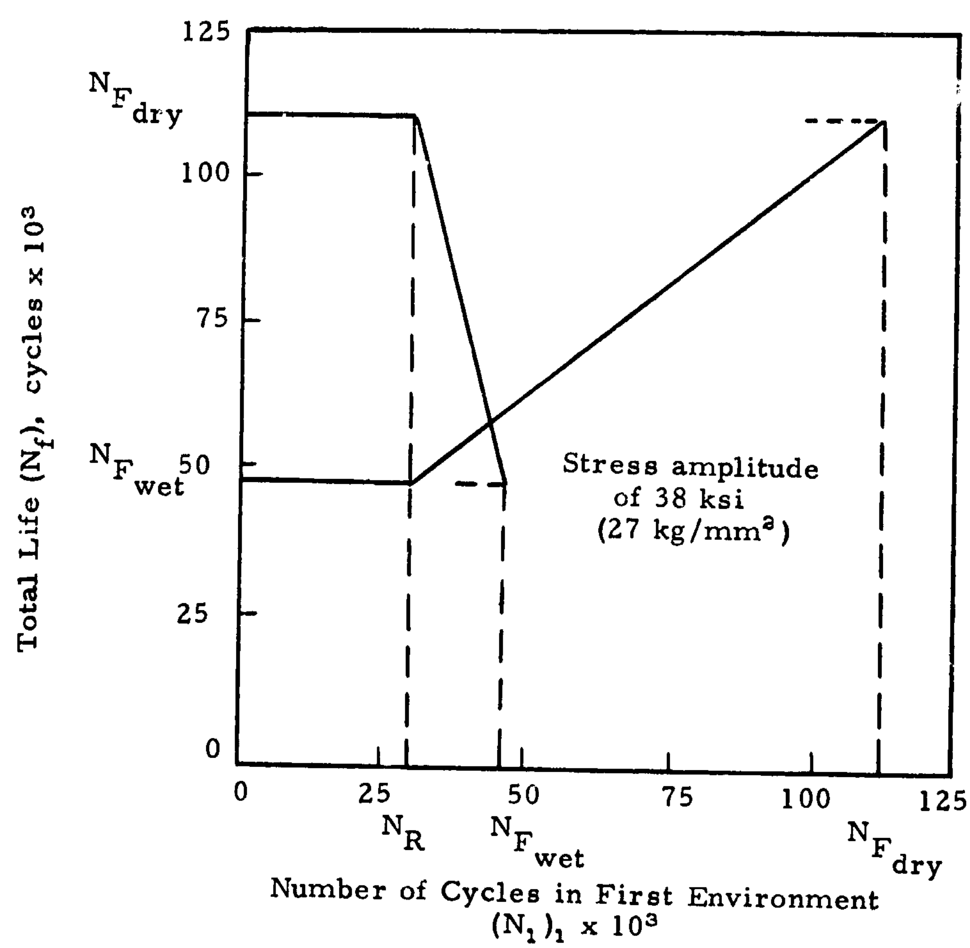

FIGURE 10.31. — Fatigue life of 6061-T6 tested in air at two moisture levels.

(Ref. 10.10)

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Chapter 11

SURFACE TREATMENTS

11.1 General. A wide variety of surface treatments can be applied to the 6061 alloy (and other aluminum alloys) to protect and improve the appearance of the surface. These include mechanical, chemical, and electrochemical finishes and organic, porcelain, and paint coatings. Alclad forms of aluminum alloys have a very high inherent resistance to corrosion and may be used without benefit of protective coating (ref. 11.1).

11.2 Alclad Products. 6061 alloy is available as Alclad sheet and plate which consists of bare 6061 core material clad with a thin coating of 7072 alloy on both sides. The clad material is metallurgically bonded to the core material. It is chosen to provide a surface having a high resistance to corrosion and sufficiently anodic to the 6061 core to afford electrochemical protection to it in corrosive environments. Consequently, any spot of attack can penetrate only as deep as the core alloy where further progress is stopped by cathodic protection. Corrosion is thus confined to the clad material only. The life of the cladding is a function of its thickness and the severity of the environment. Alclad products, therefore, limit corrosion to a relatively thin, clad surface layer (ref. 11.2).

11.3 Mechanical Finishes. Mechanical finishes are used to alter the texture of the alloy surface to provide a more decorative appearance or as a treatment prior to other finishing such as painting. Grinding, polishing, and buffing result in smoother reflective surfaces. Abrasive blasting (sand or grit) gives a rough, matte finish which is often used as a base for organic coatings. Scratch finishing, satin finishing, Butler finishing, and skin finishing are scratched line finishes which remove minor surface defects and provide a decorative effect. Mechanical methods remove the original heavy oxide film. For this reason, mechanically finished parts are often given a protective coating by anodizing or lacquering. The possibility of generating an explosive mixture of fine powder and air during mechanical finish operations should be recognized (refs. 11.3, 11.5).

11.4 Anodizing. Anodic coatings are hard, abrasion and corrosion resistant oxide coatings. The alloys can be anodically coated in a number of electrolytes, but most commercial anodizing is done by either the sulfuric acid or chromic acid process. The thickness of the coating is dependent upon the anodizing time. Coatings produced by the sulfuric acid process vary in thickness from 0.0001 to 0.001 inch (0.0025 to 0.025 mm). Coatings produced in chromic acid vary from 0.00001 to 0.00009 inch (0.00025 to 0.0023 mm). Anodic coatings provide good protection against corrosion and are excellent bases for paint coatings (refs. 11.1, 11.5).

11.41 An investigation of the anodizing of aluminum alloy extrusions demonstrated the principle that in processing through pre-anodic treatments as well as anodizing that the surface of the alloy reacts itself to form the finish. Thus, the uniformity and appearance of the resulting finish is highly dependent on the surface and the metallurgical condition of aluminum extrusions prior to anodizing. For example, a more uniform (anodized) appearance of a welded area and parent metal was obtained for 6061 when welded with 5356 filler as compared with 4043 filler (ref. 11.9).

11.5 Chemical Finishes. Chemical finishes are of three main types. Finishes used for decorative effects include caustic etching, acid etching, and chemical polishing. Etched surfaces have a matte appearance while chemically polished surfaces are highly reflective and require protection by anodizing or lacquering. Conversion coatings can be oxide, phosphate, or chromate types, and are used primarily as base coatings prior to application of organic coatings (ref. 11.5). Miscellaneous special-purpose finishes include those produced by the Alrok process, modified Bauer-Vogel process, and processes for staining aluminum alloys.

11.6 Electropolishing. This process produces a highly reflective surface and is often used for surface preparation prior to microscopic examination of metallurgical structure (see Chapter 3).

11.7 Electroplating of aluminum alloys has been used increasingly in recent years. A commonly used finish consists of successive deposits of copper, nickel, and chromium. Other metals may be applied over the copper. Several etching methods produce a satisfactory base surface for electroplating. Also used is a method involving the immersion of the aluminum part in a solution of sodium zincate of controlled composition. Brass, iron, silver, or chromium can be applied directly over this zinc immersion coating (ref. 11.5).

11.71 The results of a study designed to investigate the mechanisms of the electrodeposition of copper on the anodized surfaces of aluminum alloy 6061 indicate that the oxide film obtained with phosphoric acid is far more suitable for subsequent plating with copper than that obtained from anodizing in sulfuric acid (ref. 11.8). (It has been concluded that some alloying constituents remain in the oxide film synthesized with phosphoric acid to form the nuclei for the subsequent plating process.) Specimens anodized in a solution of 350 g phosphoric acid (H_3PO_4) per liter water for 10 minutes provided an excellent basis for subsequent smooth electrodeposition of copper from a pyrophosphate copper bath.

11.8 Painting. When severe conditions of exposure are to be encountered, it is frequently desirable to protect aluminum alloy surfaces with paint. Prior to painting, the surface should be properly prepared before priming. Dirt may be removed by brushing and grease or oil may be removed by means of solvent or degreasing techniques. The parts are then immersed in (or swabbed with) a solution of phosphoric acid and organic grease solvents diluted with water. A number of proprietary solutions of this type are available commercially. Solution temperature should be between 50° and 90°F (10° and 32°C) and contact with the metal part should not be for less than 5 minutes. The part is then rinsed with water and dried thoroughly. Where chmical treatment is impractical, mild sandblasting methods may be employed. Anodic or chemical conversion coatings form excellent bases for organic paint coatings (ref. 11.5). A zinc chromate primer, per MIL-P-8585 or equivalent, is recommended. Primer is applied to all surfaces and allowed to dry. For severe conditions of exposure, both primer and joint compound should be used at joints.

All surfaces except contacting surfaces may be given a second coat of paint consisting of two pounds (0.87 kg) of aluminum paste pigment (ASTM Spec. D962, Type II, Class B) per gallon (3.785 liters) of varnish which meets Federal Spec. TT-V-86b, Type II or equivalent. The final assembled structure may be finished with one coat of aluminum paint. One or more coats of alkyd base enamel (pigmented to desired color) may be substituted for aluminum paint.

11.81 To minimize stress-corrosion cracking when 6061 is subjected to sustained surface stresses and corrosive environments, certain surface treatments and protective coatings are reported to be effective. The most effective protection is obtained by applying a topcoat of paint containing epoxy-polyamide or polyurethane resins. The former is preferred and can be used on unprimed surfaces. Care is necessary to prevent breaking or scratching the paint film. Shot peening alone will provide good surface protection (if all surfaces are treated) when corrosive environment is not severe. Anodic films and zinc-rich paints are the least effective coatings for preventing stress-corrosion cracking (ref. 11.6).

11.9 Porcelain Enameling. The principal difference between porcelain enameling of aluminum alloys and other metals is the use of porcelain frits which melt at lower temperatures. High-lead frits are commonly used and they can be formulated in a wide variety of colors and surface finishes. The enamel slip is sprayed onto chemically cleaned and treated surfaces and then fired at temperatures of 950° to 1050°F (510° to 566°C) for a period of 4 to 8 minutes (ref. 11.7).

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Chapter 12

JOINING TECHNIQUES

12.1 General. The 6061 alloy can be readily joined by fusion and resistance welding techniques, by brazing, and by riveting or bolting. Specifications that apply to the welding of aluminum alloys are listed in table 12.1.

12.2 Welding. Reliable, sound, high quality welds have been made in aluminum alloys for many years. Although aluminum is a readily weldable metal, it has characteristics which must be understood for successful welding of the metal or its alloys. Four important factors that must be considered are the low melting point, the presence of an oxide film, low strength at elevated temperatures, and the fact that aluminum exhibits no characteristic color changes even at temperatures up to the melting point. The welding of aluminum alloys requires care to prevent excessive melting of the material. The oxide film must be removed and prevented from reforming by some inhibiting technique before a good bond can be obtained. Temperatures must be controlled by measurement rather than judged by appearance of the alloy at elevated temperatures (ref. 12.2).

The 6061 alloy exhibits good welding characteristics, when proper procedures are used, in most tempers and products welded by any of the presently used fusion and resistance welding procedures. The good resistance to corrosion of the alloy does not appear to be lowered significantly by welding processes. Thus, 6061 is an excellent choice for moderate-strength welded structures requiring high resistance to corrosion (ref. 12.16).

12.21 Fusion Welding. Aluminum alloy 6061 may be fusion welded by either the inert-gas-consumable electrode (MIG) or the inert-gas tungsten-arc (TIG) methods. The filler metal most commonly used for general purpose welding of this alloy is 4043 aluminum alloy, which provides weld zones having medium ductility and excellent resistance to cracking (ref. 12.3). Another filler metal that is sometimes employed in the fusion welding of this alloy is 5356 aluminum alloy. Fillerless fusion techniques are not recommended because of high cracking tendency. Maximum metal thickness for fusion welding is 1.0 inch (25.4 mm) (ref. 12.3).

The combined effect of porosity and mismatch has been studied for TIG welded 6061-T6 sheet (ref. 12.5). These studies have led to the conclusion that both mismatch and porosity contribute to the lowering of tensile strength of welded joints as the level of each increases in magnitude; this effect is shown in figure 12.1. Another study has indicated that there is very little depreciation of properties up to 50 percent mismatch. At 100 percent mismatch, however, an appreciable decrdase in the strength of welded material was observed as shown in figure 12.2. All specimens in this study failed at the edge of the weld or in the annealed zone areas which do not respond to aging (ref. 12.6). Data obtained in this study on tensile properties of MIG and TIG welded sheet are presented in table 12.2. These data indicate that automatic processes were definitely superior to manual TIG welding. They also indicate that repair welding may lead to a loss in strength and the degree of loss is dependent upon the number of repairs. In another study, however, semiautomatic MIG weld repairs on 6061-T6 plate were preated up to 6 times with little observed effect. No thermal treatment was applied subsequent to welding or repair welding. The only evidence of an effect of rewelding was a slight loss in tensile strength of the plate at distances of 1/2 and 1 inch (12.7 and 25.4 mm) from the weld for 2 or more rewelds. The effect of the heat due to welding did not extend more than 1-1/2 inches (38.1 mm) from the weld centerline. The filler metal employed in this study was the 5356 alloy.

The effect of test temperature on the tensile properties of TIG butt-welded sheet is illustrated in figures 12.3 and 12.4. Typical stress-strain curves for both unwelded and TIG welded sheet are shown in figure 12.5. Bulge test results for T4 and T6 TIG welded sheet are presented in figure 12.6.

The effect of welding speed on the tensile strength of weld specimens is shown in figure 12.7. These data indicate that the strength is increased as the weld speed becomes larger, and the strength approaches the base metal strength at high weld speeds.

12.22 Electrical Resistance Welding. Resistance welding (spot welding and seam welding) is a most useful and economic method of joining aluminum alloys. The welding process is almost entirely automatic and standard welding machines are capable of handling a wide variety of operations. Resistance welding heats only a small area of metal for a short length of time, thereby producing a narrow heat affected zone. Consequently, base material properties are not significantly affected. Maximum metal thickness for spot and scan welding is 3/16 inch (4.76 mm) (ref. 12.3).

Mechanical or chemical cleaning of the contact surfaces is necessary to obtain good spotwelds in aluminum because no fluxes are used during spotwelding. In aircraft construction, it is recommended that the contact resistance of the elements to be joined by checked continually as a measure of surface cleanliness. Surface contact resistance should not exceed 50 microhms for best results. Details on surface cleaning are given in reference 12.3.

Aluminum 6061 alloy, in all heat treated tempers, can be successfully spotwelded but special practices are required, and the range of machine settings is rather narrow. Precleaning is necessary for sound consistent welds. In the annealed condition, the alloy is somewhat difficult to weld and spotwelding in this condition is not recommended. Spotwelded 6061 alloy has excellent resistance to corrosion in all tempers. Alloy 6061 may be joined by spotwelding to aluminum alloys 1100, 3003, 5052, 2014, 2024, 7075, Clad 2014, Clad 2024, Clad 7075, and to itself (refs. 12.3, 12.8). The choice of the type of resistance welding machine for spot or seam welding of aluminum alloys depends partly on the power supply, its voltage drop characteristics, demand limitations, and other similar factors. A detailed discussion of resistance welding is given in reference 12.3.

12.221 Mechanical Properties of Spot Welds. The use of spot welds on military structural parts is governed by the requirements of the procuring or certificating agency (ref. 12.8). The requirements for equipment, materials, and production control of spot and seam welds are covered by military specification MIL-W-6858B-1 (see table 12.1).

The minimum distance suggested for joint overlap and spotweld spacing is presented in table 12.4 for a number of sheet thicknesses. The minimum allowable edge distance for spotwelded joints is also given in table 12.4. Table 12.5 gives design shear strength allowables for spotwelds in bare and clad alloys; the thickness ratio of the thickest sheet to the thinnest outer sheet in the combination should not exceed 4:1. In applications of spotwelding where ribs, intercostals, or doublers are attached to sheet, either at splices or at other points on the sheet panels, the allowable ultimate strength of the spotwelded sheet should be determined by jultiplying the ultimate tensile sheet strength (MIL-Hdbk-5A "A" values where available) by the appropriate efficiency factor as given in figure 12.8. The minimum values of the basic sheet efficiency in tension should not be applied to seam welds. Allowable tensile strength values for spotwelded sheet less than 0.020 inch (0.508 mm) should be established on the basis of tests acceptable to the procuring or certificating agency (ref. 12.8).

The fatigue strength of triple-row spotwelded lap joints is shown in figure 12.9 for sheet in the T6 condition.

12.3 Brazing. The 6061 alloy exhibits excellent brazeability in the T4 and T6 conditions and is generally brazeable by all commercial procedures and methods. The recommended brazing alloy is Alcoa 718 used in conjunction with flux number 33 or 34. Flux No. 33 is normally used for torch or furnace brazing and flux No. 34 is employed for dip brazing. The optimum brazing temperature range is 1080°–1095° F (582°–591° C). Specifications for brazing flux and filler metals are listed in table 12.6. Strong brazed joints depend on correct procedures, starting with clean surfaces. All oil and grease must be removed. Chemical cleaning is usually required and several proprietary cleaners are commercially available for this purposes. Mechanical processes such as wire brushing may also be used. Parts should generally be brazed within 48 hours after cleaning. All brazing operations require flux and the operation depends upon capillary action to draw filler metal into the joint. Clearances for flow of metal and escape of flux should be considered in the design of the joint as entrapped flux is a potential corrosion hazard.

The actual brazing temperature in most cases should be high enough to melt all of the filler metal. This is best determined by trial, using a thermocouple to measure the temperature.

A number of brazing techniques are used, depending upon the particular application. Among these are:

- Torch brazing (oxyacetylene etc.)
- Furnace brazing
- Dip brazing
- Specialized processes (such as mechanized flame, induction brazing, block brazing, and metal dip brazing).

A detailed discussion of these processes and the brazing of aluminum alloys is found in reference 12.9.

12.4 Riveting. Riveting is a commonly used method for joining aluminum, particularly the heat-treatable alloys. It is reliable because riveting is a method that is well understood and highly developed. Also, modern riveting methods are largely independent of operator skill and thus uniformity of riveted joints can be readily attained (ref. 12.2). Specifications for aluminum riveting are presented in table 12.7.

12.41 Aluminum alloy rivets are preferred for the fabrication of aluminum alloy structures, although cold-driven annealed steel rivets have been used successfully for some applications. To determine the strength of riveted joints, it is necessary to know the strength of the individual rivet. The average shear strengths for driven rivets of various aluminum alloys are given in table 12.8. In most cases, such joints fracture by shearing, by bearing or tearing failure of the sheet or plate. It is customary to use a slightly larger factor of safety for the shear strength of rivets than is employed for other parts of an assembly. The design of joints where rivets are subjected to tensile loads should be avoided. Bolted connections may be used where high tensile stresses preclude the use of riveting. Information in greater detail on the riveting of aluminum alloys is given in references 12.10 and 12.11. Design data on mechanical joints using rivets or bolts may be found in Mil-Hdbk-5A (ref. 12.8).

TABLE 12.1. — Welding Specifications

Source	Refs. 12.1, 12.12, 12.13, 12.14			
Product or process	Federal	Military	ASTM	AMS
Weldments (aluminum and aluminum alloys)	-	MIL-W-22248	-	-
Welding of aluminum alloys	-	MIL-W-8604	-	-
Welding (aluminum alloy armor)	-	MIL-W-45206	-	-
TIG welding, aluminum alloy for structures	-	MIL-W-45205	-	-
Welding; resistance, aluminum alloys	-	MIL-W-45210	-	-
Welding; spot, seam, or stitch (Al, steel, Mg, Ti)	-	MIL-W-6858	-	-
Welding rods (aluminum)	QQ-R-566	-	B285	4190B, 4191A
Welding electrodes (flux coated)	-	MIL-E-15597	B184	-
Welding electrode wire	-	MIL-E-16053	B285	-
Flash welds (rings, flanges)	-	-	-	7488C

TABLE 12.2. — Tensile Properties of TIG and MIG Welded Sheet

Source	Ref. 12.6											
Alloy	6061-T4 aged to T6											
Thickness	0.050 inch (12.7 mm)						0.125 inch (31.8 mm)					
Data (e)	F_{tu}, ksi		F_{ty}, ksi		e, %		F_{tu}, ksi		F_{ty}, ksi		e, %	
Orientation	L	T	L	T	L	T	L	T	L	T	L	T
Weld Process												
Manual TIG	27.3	26.9	22.0	21.5	2.8	2.2	28.1	29.0	20.3	20.3	5.6	3.8
Auto-TIG	43.1	42.3	38.8	37.2	6.7	7.0	50.1	50.2	46.8	45.4	8.3	9.8
(a)	39.4	39.1	36.3	36.1	3.4	3.4	37.1	33.0	33.9	27.5	3.0	3.2
(b)	38.0	35.5	35.3	32.7	2.2	2.0	33.5	32.7	27.5	27.1	4.0	4.0
MIG Welds	-	-	-	-	-	-	42.0	41.9	39.2	38.3	3.9	4.0
(c)	-	-	-	-	-	-	35.2	36.3	30.4	32.4	3.0	3.0
(d)	-	-	-	-	-	-	32.4	32.7	25.7	26.8	3.5	3.8

(a) Automatic TIG welded plus one repair weld.
(b) Automatic TIG welded plus two repair welds.
(c) MIG welded plus one repair weld.
(d) MIG welded plus two repair welds.
(e) 1 ksi = 0.70307 kg/mm^2
Each value is average of 6 tests. 4043 filler wire was used for all welds. Aging treatment: 340°-355°F(171°-179°C), 8 hrs. After welding, no solution treatment was employed.

TABLE 12.4. – Suggested Minimum Joint Overlap and Weld Spacing, and Minimum Allowable Edge Distances for Spotwelded Joints

Source	Refs. 12.3, 12.8		
Alloy	Aluminum Alloys		
Nominal thickness of thinner sheet, inch	Minimum joint overlap, inch	Minimum weld spacing, inch	Edge distance, E (min), inch
0.016 (d)	5/16	3/8	(a, 3/16
0.020	3/8	3/8	b, 3/16
0.025	3/8	3/8	c) 7/32
0.032	1/2	1/2	1/4
0.036	-	-	1/4
0.040	9/16	1/2	9/32
0.045	-	-	5/16
0.050	-	-	5/16
0.051	5/8	5/8	-
0.063	-	-	3/8
0.064	3/4	5/8	-
0.071	-	-	3/8
0.072	13/16	3/4	-
0.080	-	-	13/32
0.081	7/8	3/4	-
0.090	-	-	7/16
0.091	15/16	7/8	-
0.100	-	-	7/16
0.102	1	1	-
0.125	1-1/8	1-1/4	9/16
0.160	-	-	5/8

(a) Intermediate gages will conform to the requirement for the next thinner gage shown.

(b) Edge distances less than those specified above may be used provided there is no expulsion of weld metal or bulging of the edge of the sheet or damage to bend radii by electrode

(c) Values may be reduced for nonstructural applications or applications not depended on to develop full weld strength

(d) 1 inch = 25.4 mm

[Ref. 12.3, overlap and spacing; ref. 12.8, edge distance]

TABLE 12.5. — Spot Weld Maximum Shear Strength Standards (a)

Source	Ref. 12.8			
Alloy	Aluminum Alloys, (bare and clad)			
Nominal thickness of thinner sheet, inch (b)	Material ultimate tensile strength, lb (c)			
	Above 56 ksi (d)	28 to 56 ksi	20 to 27.5 ksi	≤ 19.5 ksi
0.012	60	52	24	16
0.016	86	78	56	40
0.020	112	106	80	62
0.025	148	140	116	88
0.032	208	188	168	132
0.040	276	248	240	180
0.050	374	344	321	234
0.063	539	489	442	314
0.071	662	578	515	358
0.080	824	680	609	417
0.090	1002	798	695	478
0.100	1192	933	750	536
0.112	1426	1064	796	584
0.125	1698	1300	840	629
0.160	2490	-	-	-
0.190	3230	-	-	-

(a) The reduction in strength of spotwelds due to cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.

(b) 1 inch = 25.4 mm

(c) 1 lb = 0.4536 kg

(d) 1 ksi = 0.70307 kg/mm^2

TABLE 12.6. — Specifications for Brazing Flux and Filler Metal

Source	Ref. 12.9
Alloy	Aluminum Alloys
Specification	Description
ASTM B260 and AWS-A5.8	Tentative Specification for Brazing Filler Metal
AMS 3412	Flux - Aluminum Brazing (Alcoa No.33)
AMS 4184A	Aluminum Alloy Brazing Wire (No.716)
AMS 4185	Aluminum Alloy Brazing Wire (No.718)
AMS 4190A	Aluminum Alloy Welding Wire (4043)

TABLE 12.7. — Specifications for Aluminum Rivets

Source	Ref. 12.1		
Products	Federal	Military	AMS
Rivets	FF-R-556	MIL-R-1150	7220
	-	MIL-R-5674	7222
	-	MIL-R-12221	7223
Rivets, blind	-	MIL-R-7885	-
	-	MIL-R-8814	-
	-	MIL-R-27384	
Rivet, wire	QQ-A-430	-	-

TABLE 12.8. – F_{su} (Average) for Driven Rivets (c)

Source	Ref. 12.10		
Alloy and Temper before Driving (a)	Driving Procedure	Alloy and Temper after Driving	F_{su} (av) ksi (d)
1100-H14	Cold, as received	1100-F	11
2017-T4	Cold, as received	2017-T3	39
2017-T4	Cold, immediately after quenching	2017-T31	34(b)
2024-T4	Cold, immediately after quenching	2024-T31	42(b)
2117-T4	Cold, as received	2117-T3	33
5056-H32	Cold, as received	5056-H321	30
6053-T61	Cold, as received	6053-T61	23
6061-T4	Cold, immediately after quenching	6061-T31	24(b)
6061-T4	Hot, 990° to 1050°F (532°–566°C)	6061-T43	24(b)
6061-T6	Cold, as received	6061-T6	30
7277-T4	Hot, 850° to 975°F (454°–524°C)	7277-T41	38

(a) These designations should be used when ordering rivets.

(b) Immediately after driving, the shear strengths of these rivets are about 75% of the values shown. On standing at ambient temperatures, they age harden to develop full shear strength. This action takes about 4 days for 2017-T31 and 2024-T31 rivets. Values shown for 6061-T31 and 6061-T43 rivets are attained in about 2 weeks. Values of 26 ksi are attained by 6061-T31 rivets about 4 months after driving. Values shown for 7277-T41 rivets are attained in about one week.

(c) These values are for rivets driven with core point heads. Rivets driven with heads requiring more pressure may be expected to develop slightly higher strengths.

(d) 1 ksi = 0.70307 kg/mm^2

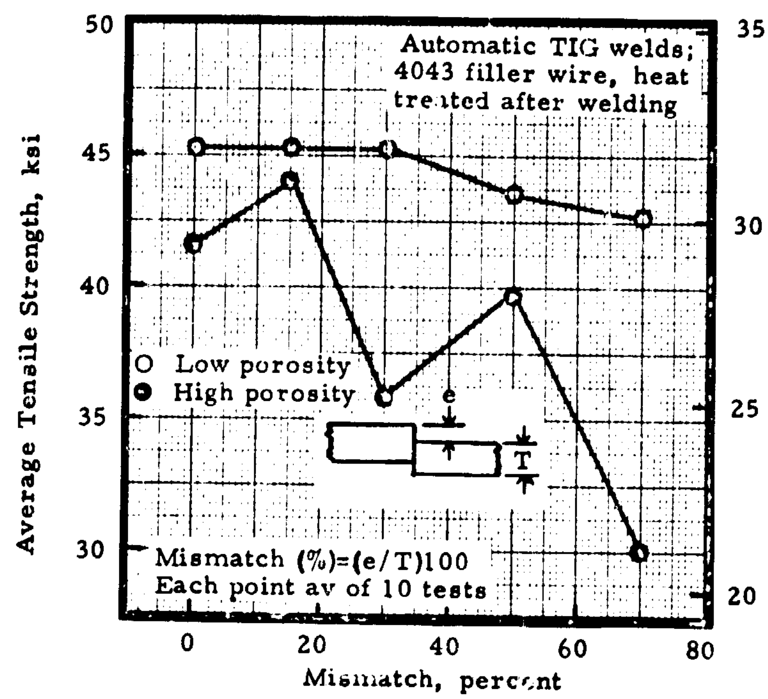

FIGURE 12.1. – Combined effect of porosity and mismatch for TIG welded 6061-T6 sheet, 0.100 inch (2.54 mm).

(Ref. 12.5)

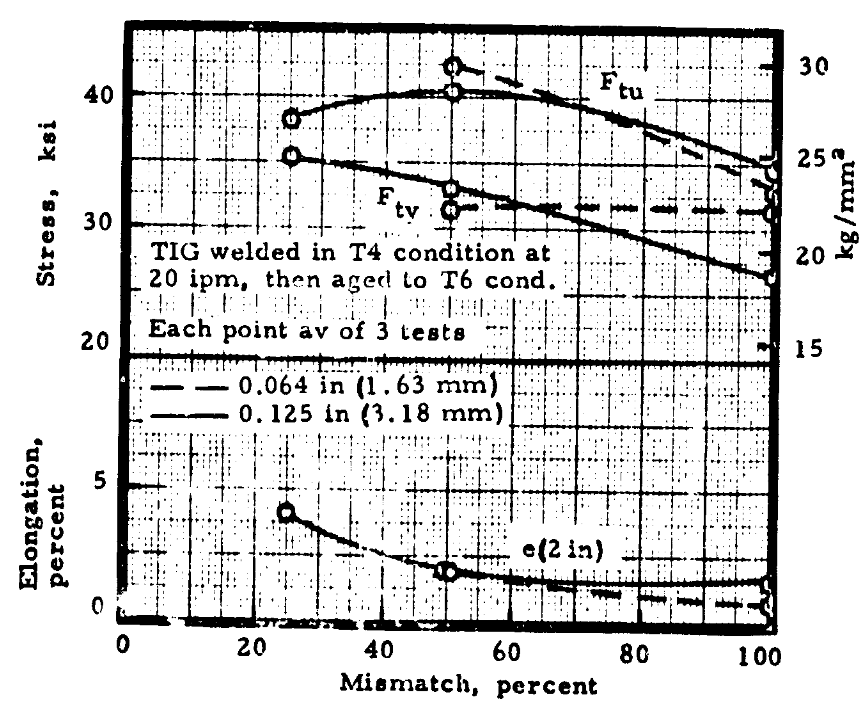

FIGURE 12.2. – Effect of mismatch on tensile properties of TIG butt-welded 6061-T6 sheet.

(Ref. 12.6)

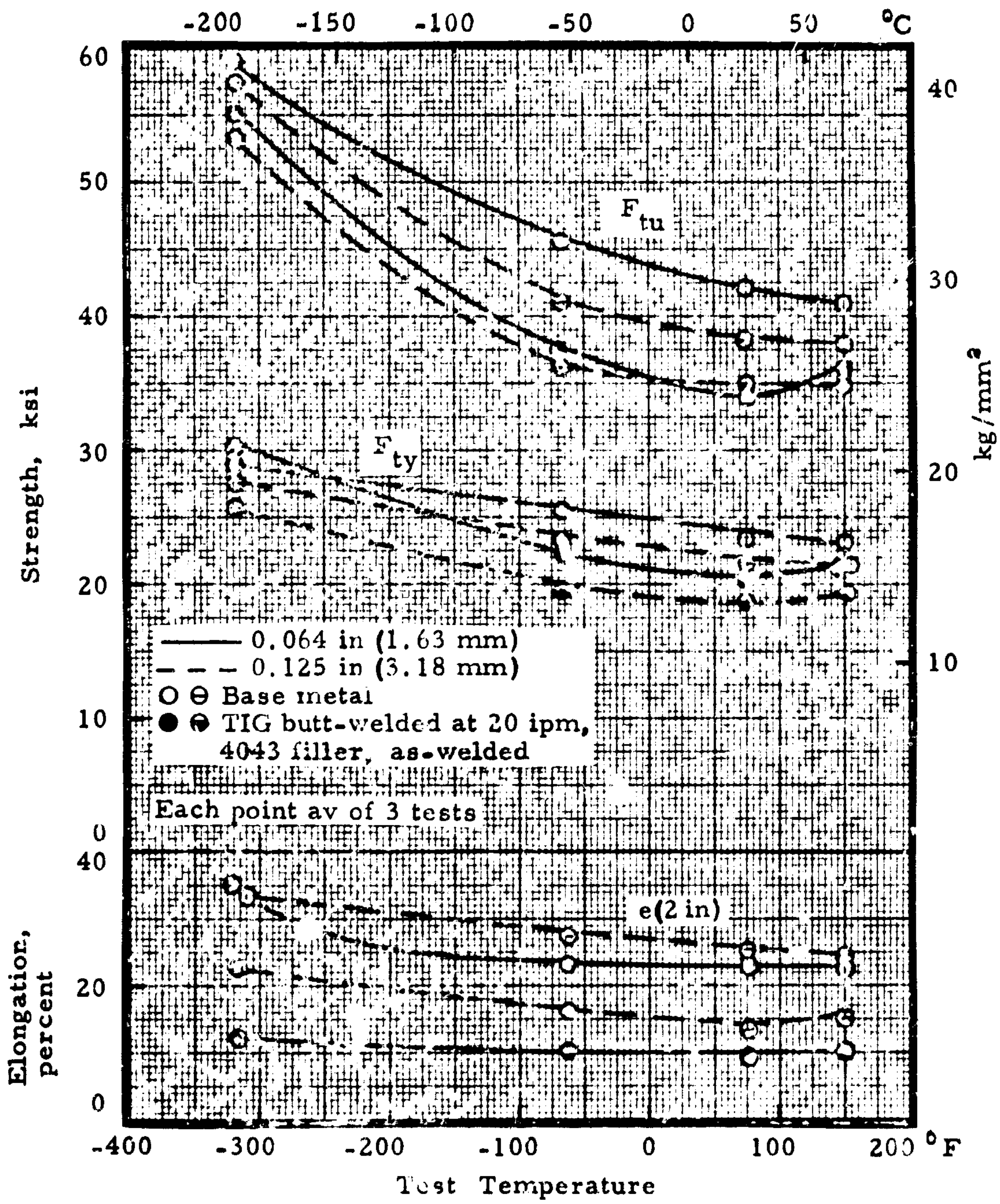

FIGURE 12.3. – Effect of temperature on tensile properties of TIG butt-welded 6061-T4 (transverse).

(Ref. 12.6)

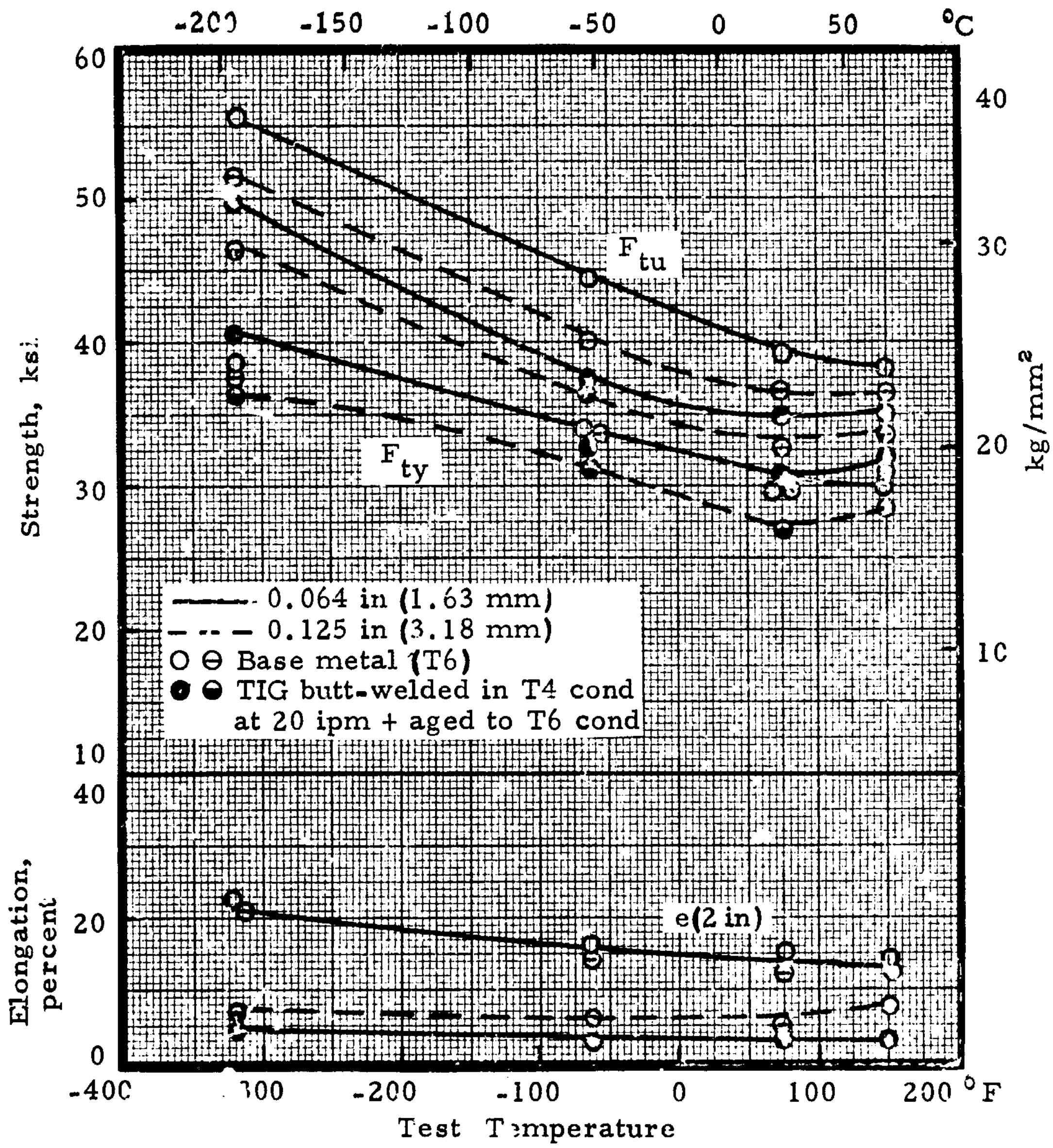

FIGURE 12.4. — Effect of temperature on tensile properties of of TIG butt-welded 6061-T4 sheet, aged to T6 (transverse).

(Ref. 12.6)

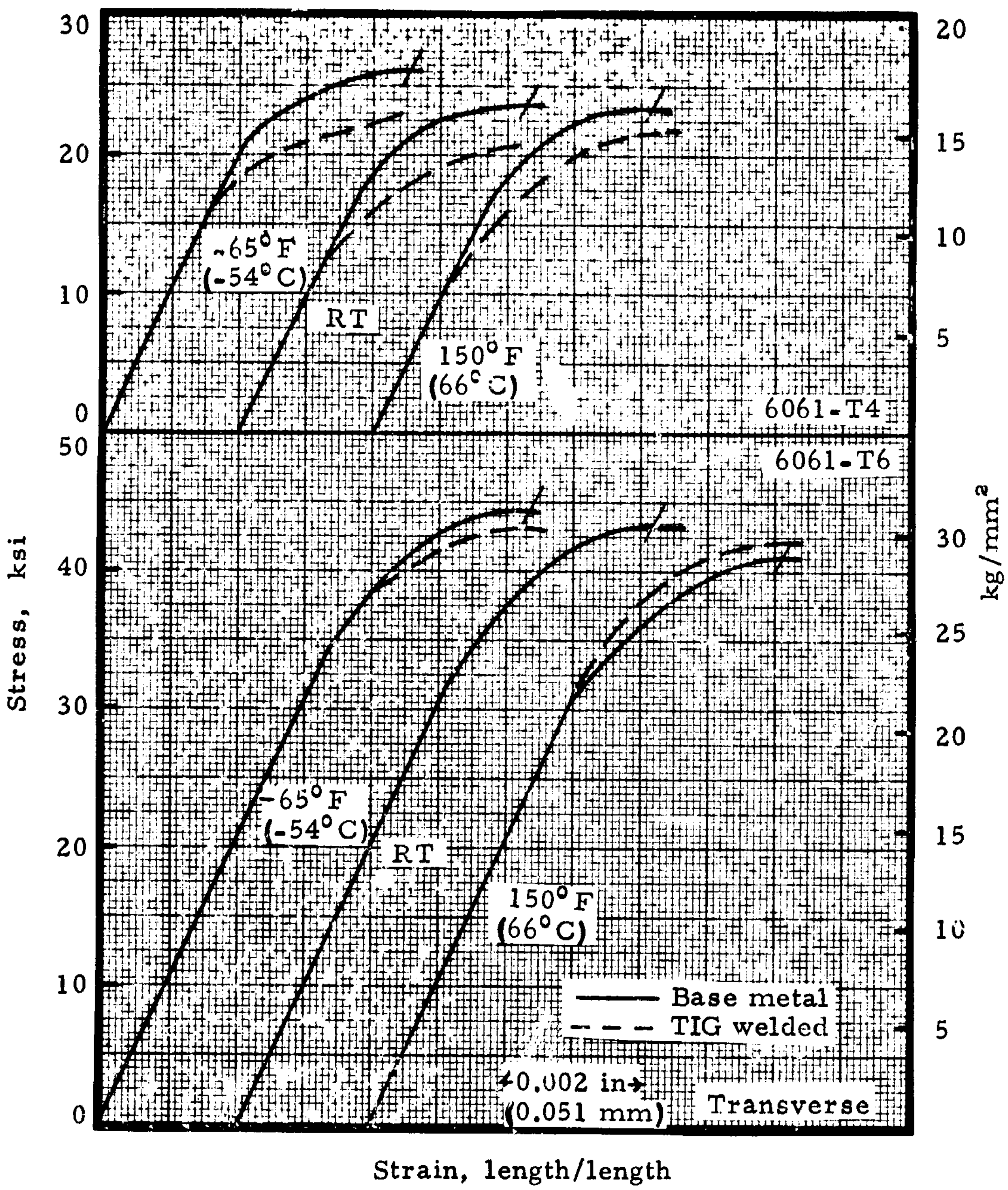

FIGURE 12.5. – Typical stress-strain curves for unwelded and TIG welded 6061 sheet at various temperatures, 0.064 in (1.63 mm).

(Ref. 12.6)

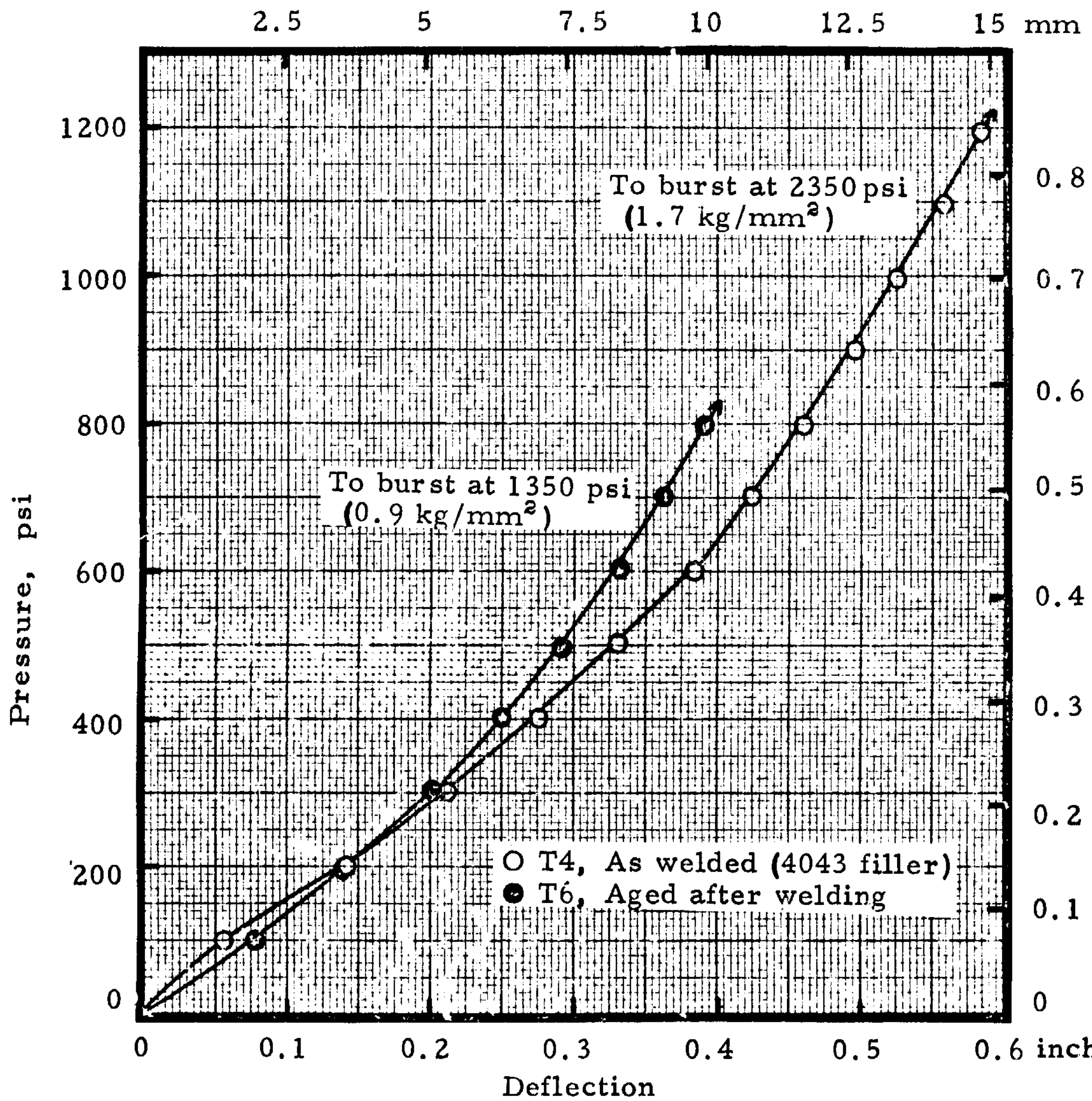

FIGURE 12.6. – Bulge test results for 6061-T6 and 6061-T4 welded sheet, 0.125 in (3 175 mm).

(Ref. 12.6)

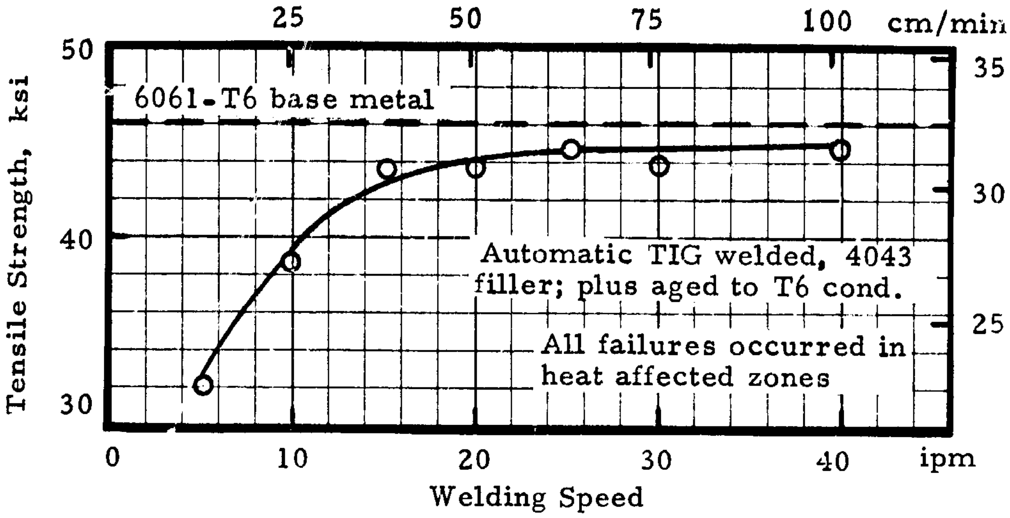

FIGURE 12.7. – Effect on welding speed on tensile strength of 6061-T4 aged to 6061-T6.

(Ref. 12.7)

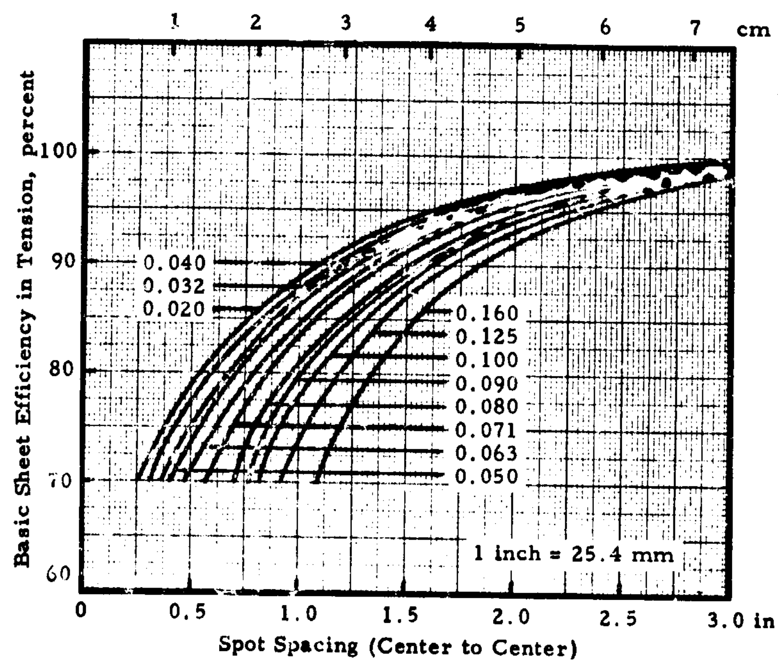

FIGURE 12.8. – Efficiency of the parent metal in tension for spot welded aluminum alloys.

(Ref. 12.8)

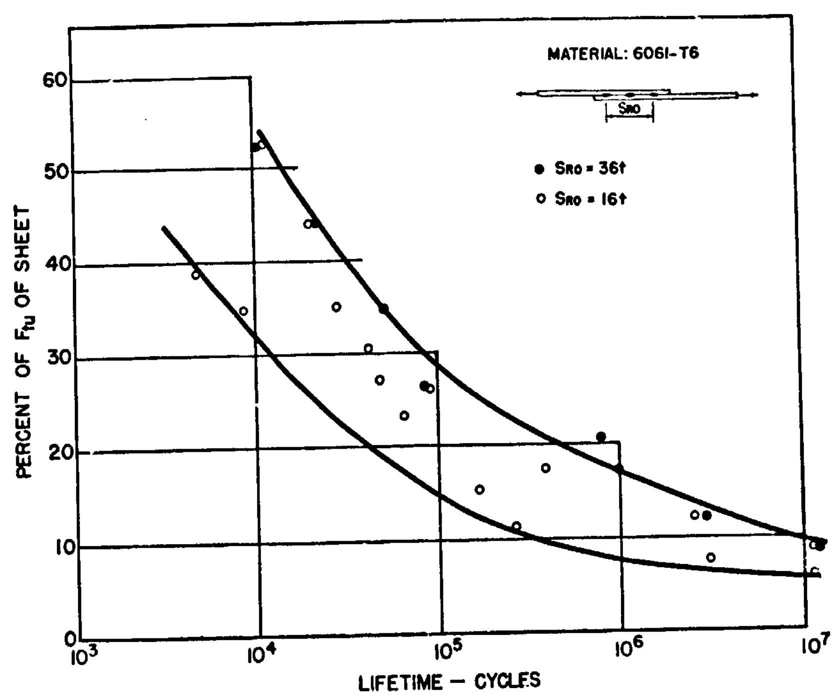

FIGURE 12.9. — Fatigue strength of triple row spot welded lap joints in 6061-T6 sheet. Load ratio = 0.05 (static failure by tear in sheet).

(Ref. 12.8)

Chapter 12 - References

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